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ALIEN ODDS TAKE A HIT

New evidence shows how rare Earth is

THE LAST OF OUR KIND

How humans won out

A STRANGE DEVELOPMENT

When the body's organs are reversed



Inside Your Memories

YOUR PAST IS OPEN TO INTERPRETATION p.22



ISSUE 58

Science Connected

NAUTILUS



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Forever Young

BY KEVIN BERGER

WITH HIS WONDERFUL SARCASM, neuroscientist Robert Sapolsky once told me about a “half-assed study I did in this technical journal, *The New Yorker*.”

Sapolsky wanted to know why teenagers were open to new experiences and he, then in his 40s, was becoming closed to them.

To begin with, Sapolsky wanted to figure out when we form our musical tastes and when we stop being open to new music. In the late 1990s, his research assistants at Stanford University called radio stations that specialized in music of various periods: modern rock, classic rock, light rock, oldies from the '50s.

After more than 40 phone calls, Sapolsky wrote in *The New Yorker* in 1998, a pattern became clear: “not a lot of 17-year-olds were tuning in to the Andrews Sisters, not a lot of Rage Against the Machine was being played in retirement communities, and devotees of 60 nonstop minutes of James Taylor were starting to wear relaxed-fit jeans.”

To put a fine point on it, Sapolsky wrote, “Most people are 20 years old or younger when they first hear the popular music they choose to listen to for the rest of their lives.” (In this issue’s cover story about the interpretative nature of memory, Sapolsky spells out the neurobiology of why that should be.)

“It’s amazing,” said Sapolsky, who studied baboons in the wild for years. “A baboon who has transferred into a new troop where there’s new foods, if they’re adolescent, will try it; if they’re adult, no. The same is true in a lot of species. Early on, in young adulthood, there’s a craving for novelty, and then for most of us, the window mostly closes.”

“That’s not true for me,” I told Sapolsky. “I seek new experiences, especially in music, all the time.”

“Wow, good for you,” he said. I couldn’t tell if he was impressed or didn’t believe me.

I have always thought that seeking new experiences is my job as a journalist and person. Although I shouldn’t say “job” because I never feel it is. I am lucky to have a temperament, shaped by whatever forces, that make me curious about most everything. I seek new experiences in the arts and sciences with the same zeal.

I recently attended a talk between novelists Marlon James and Richard Powers at the New York Public Library. (You can read Powers on his new novel, *Playground*, in this issue.) James, author of the Booker Prize-winning *A Brief History of Seven Killings*, about Bob Marley and Jamaica, had a wry and acerbic manner. “What is the one trait in people I absolutely cannot stand and cannot get past? ‘Uncuriosity,’” he said. “The idea, ‘I know enough,’ I’ve never understood that.” Neither have I.

James read Powers a question from an audience member, who asked what role spirituality played in his science-steeped novels. A premise of the question, Powers pointed out, was that our emotional and intellectual lives were separate. They weren’t.

“The best writers of science have always known that the only thing that’s going to save us is the power of empirical investigation wedded to the power of spiritual introspection,” Powers said. “If these two are seen as separate and inimical things, we will die. If they’re seen as flip sides of the same human urgency, we might stick around a little bit longer.”

Creating articles that marry science and introspection has been my goal at *Nautilus* since our inception. We may not save the world. But with articles that inform and enchant, we’re trying.



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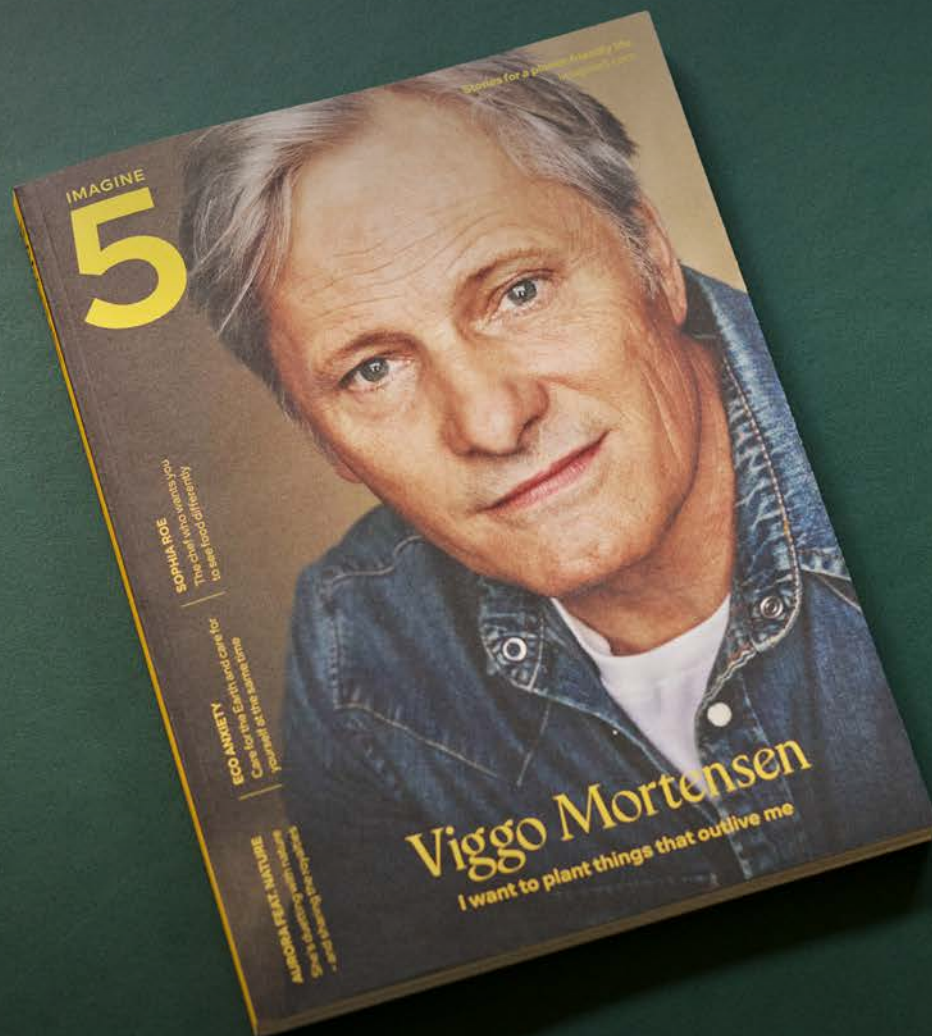
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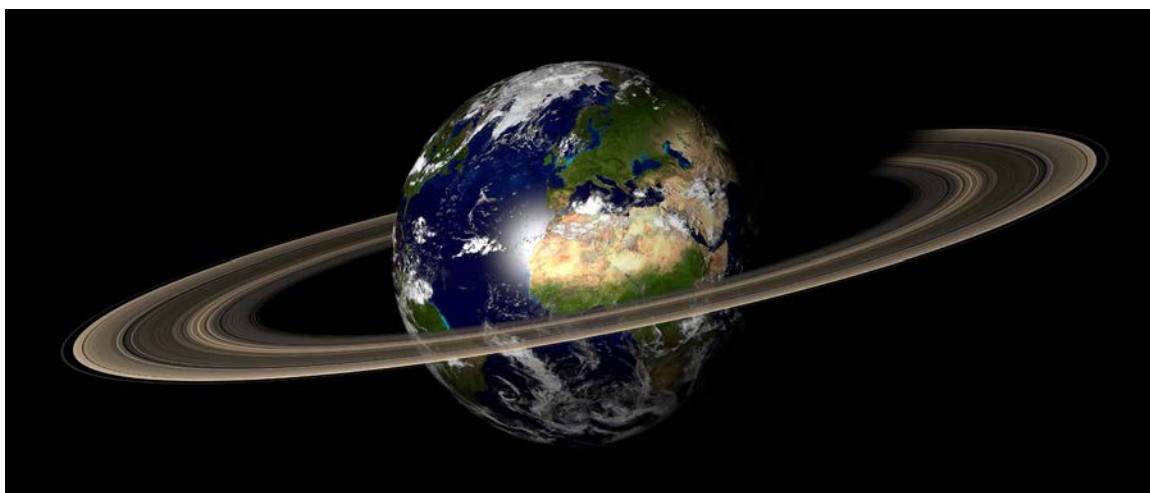
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THE PORTHOLE

Short sharp looks at science



GEOSCIENCE

When Earth Had Rings

PLANETARY RINGS MAY BE one of space's many spectacles, but in our solar system, they're a dime a dozen. While Saturn's rings are the brightest and most extensive, Jupiter and Uranus and Neptune have them, too. What's more, four icy minor planets—Chariklo, Chiron, Quaoar, and Haumea—that orbit among or beyond our gas giants, also host ring systems. Even so, it would be fanciful to imagine that Earth once had a ring system of its own, wouldn't it? I mean, that just seems almost too cool to be true.

Or is it?

Rings are likely the dwindling remains of shredded asteroids or comets, and when you think about the turbulence Earth experienced around half a billion years ago, the reality of a bygone ring system around Earth seems less farfetched. That's the case researchers make in a new study published in *Earth and Planetary Science Letters*.

About 466 million years ago (long before the dinosaurs), the rate of stuff falling on Earth that was large enough to leave craters spiked sharply. Researchers have identified 21 impact craters from this spike, with sizes between a few and 50 kilometers in diameter.



If Earth went through one ringed phase, there's a good chance it went through several.

And sedimentary rocks from this period show a huge increase—a factor of 100 to 1,000—in the concentration of elements associated with a specific group of meteorites, called L chondrites. This period, the mid-Ordovician, also included an extreme drop in global temperature, roughly 10 degrees Celsius, which coincided with increased seismic and tsunami activity. Also, a mass extinction eliminated 85 percent of marine species, after which the temperature rebounded. What could possibly explain this?

The authors of the new study, led by Andy Tomkins, a geoscientist at Monash University in Australia, claim that you can account for the craziness of the Ordovician period if Earth had a system of rings that it captured from an asteroid. And if it went through one ringed phase, there is a good chance that it went through several. And for good measure, the other rocky planets may have done the same.

"This opens up a new way of thinking about the history of the Earth," Tomkins wrote in an email. He and his colleagues focused on the distribution of craters on Earth during the Ordovician's impact spike. The craters are spread across Earth's surface, but its tectonic plates—the movement of which pushes the continents around—have shifted considerably in the last 450-plus million years.

The researchers determined where the impacts actually took place by "rewinding the clock" of the continents' movements using computer models of how the Earth's surface has rearranged itself. This showed that all of the crater-forming collisions took place within a narrow band centered on the equator. They gathered the data on where craters are located today (across the

globe, especially in areas that were not likely to have been covered in ice during the Ordovician, given that ice could prevent crater formation), while also taking into account the regions where such craters could not have been found (due to present-day ice coverage, such as in Antarctica), and where craters could not have been preserved because of processes such as burial and erosion. Putting all of these factors together, Tomkins and his colleagues calculated that it would be highly improbable—we're talking about a 1 in 25 million chance—that the impacts were randomly distributed across the Earth's surface.

To explain why the impacts are concentrated at the equator, Tomkins and his colleagues proposed that the Ordovician Earth had a system of rings. The Ordovician impacts came from objects within the rings that crashed down onto Earth. Saturn's rings are thought to have formed from a large icy object that passed so close to Saturn that it was torn into pieces in a process called tidal disruption. When a comet or asteroid passes very close to a planet, the difference in gravity across the object is strong enough to stretch it to its breaking point.

We have seen tidal disruption in action: In 1992, the comet Shoemaker-Levy 9 passed so close to Jupiter that it was torn into a string of about 20 fragments. Most of these rained down onto Jupiter in 1994. In the case of Saturn's rings, the shards of the disrupted object were captured into orbit. The orbits of captured fragments would have started off being extremely stretched-out, or eccentric, and aligned with the initial orbital trajectory of the icy parent body. In time, the ring fragments collided with each other and were ground down to smaller pieces, and the collection of objects settled to a circular system of rings aligned with the plane of Saturn's equator, where we see them now.

The ring-producing asteroid must have been an L chondrite, a type of ordinary meteorite ("ordinary" because they are the most common type of meteorites in our collections). Tomkins and his colleagues suggest that the L chondrite parent body passed extremely close to Earth—within just a few thousand kilometers of the surface, scratching the edge of the atmosphere—and was tidally disrupted, just like the object that broke apart and formed Saturn's rings. Its fragments settled to Earth's equatorial plane, and dust from the ring

slowly rained down on Earth, along with the occasional impact of a larger fragment, mostly near the equator. This explains the high concentrations of L chondrite meteorite-like dust in Ordovician sedimentary rocks, as well as the distribution of craters across the globe.

The sharp drop in temperature after the Ordovician impact spike—called the Hirnantian global icehouse—may also have been a consequence of the Earth’s rings. The rings’ shadow would have fallen on whichever hemisphere was in winter at that time, and would have had a net cooling effect, which the dust in the atmosphere may have amplified. This drastic cooling perhaps played a role in the late Ordovician mass extinction: The global temperature bounced back up after the end of the Ordovician impact spike, presumably due to the dissipation of the rings.

“It seems plausible that the planets have seen multiple cycles of ring formation and loss,” Tomkins wrote in an email. These cycles would be triggered by the rare, very close passage of a comet or asteroid. Some planets

are more likely to have ring phases than others, based on the frequency of asteroid flybys and the planets’ properties. Jupiter, Saturn, Uranus, and Neptune seem to have more frequent, or longer-lived, ring phases because they interact far more frequently with asteroids and comets than the rocky planets, and so have far more chances of disrupting one and capturing its fragments. Ring phases usually last for millions of years at a time, with considerable consequences for a planet’s geology, climate, and potentially life.

For Tomkins, the search is underway for other potential pieces of evidence that Earth has undergone previous ring phases. The Ordovician spike is the clearest sign so far. “The cratering record gets weaker the further back in time we look,” he wrote in an email. “What other evidence can we look for that Earth may have had this and other rings in the past?”

It’s a good question. And I’m excited to know someone like Tomkins is out there chasing down an answer.

—Sean Raymond

PSYCHOLOGY

Falling Down a Rabbit Hole in Real Life

IMAGINE, AS YOU’RE GETTING UP from the dinner table, you look down and notice that the apple on your plate is suddenly enormous, the size of a tortoise. When you rise from your chair, you feel your legs are three times longer than normal—as though you were dangling on stilts above the table and the now monstrous fruit. If this happened to you, you might begin to suspect that you had slipped down the rabbit hole into Lewis Carroll’s *Wonderland* along with Alice.

Neurologist Maximilian Friedrich first heard this very anecdote from his great-grandmother when he began studying perception. She had experienced it decades earlier when she was a mother suffering from migraines, but it never happened again and she kept it a secret—there was too much stigma around illnesses





of the mind at the time. Today, her great-grandson is a researcher at University Hospital Wuerzburg in Germany—and he studies what has become known as Alice in Wonderland syndrome.

“Their world really warps—it’s such an uncanny experience,” says Friedrich. Neurologists don’t understand the syndrome, and Friedrich wanted to change that.

It may be a lot more common than we think. Though just 200 individual cases have been reported since the 1950s, recent studies suggest that up to 20 percent of migraine patients may suffer from the syndrome, while evidence suggests that up to 30 percent of adolescents have experienced some of its symptoms. Some sufferers see figures with extra body parts, feel that walls are closing in, or it may sound to them as though other people are talking unnaturally fast or slow. The episodes usually pass in a matter of minutes, and no medical tests can so far diagnose these events.

Such perceptual distortions may have inspired Carroll, whose protagonist Alice, in his 1865 children’s book *Alice’s Adventures in Wonderland*, senses her own body growing larger and smaller in the fantasy world of Wonderland. (Carroll also reportedly suffered from migraines, but it’s not clear whether he experienced the syndrome itself.) English psychiatrist John Todd was the first to give the syndrome a name, almost a century later, in 1955. Today it is defined as a disorder involving perceptual distortions of size and scale, particularly of one’s own body, objects in the environment, or of time.

A new study co-authored by Friedrich is one of the first attempts to shed light on neurological networks that may be associated with some of its symptoms. The researchers mapped certain circuits in the brains of 37 individuals who have experienced Alice in Wonderland syndrome. What they found may shed light not only on how it arises, says Friedrich, but on human perception more generally.

Friedrich’s great-grandmother had a migraine right after her experience, and migraine is considered the number one cause of the disorder’s symptoms. But migraine doesn’t leave the kind of trace that can be picked up by functional magnetic resonance imaging scans, which makes it difficult to research these patients.

Evidence suggests that lesions in the brain produced by a stroke or brain bleeding are the second most common cause of the syndrome. So Friedrich and his

Some sufferers see figures with extra body parts, feel that walls are closing in.

colleagues mapped the lesions found in the study participants and then examined existing fMRI data about which brain networks most commonly connect to the locations of the lesions. They found that over 85 percent of the lesion locations shared connections to two specific hubs in the brain: the right extrastriate body area, known to be involved in viewing body parts, and the inferior parietal cortex, known to be involved in judgments of scale and size. The research was published this summer in the journal *Annals of Neurology*.

“These are truly novel findings which I expect to have substantial implications for further research on Alice in Wonderland syndrome, and hopefully also for patient care,” says Jan Dirk Blom, a professor of clinical psychopathology at Leiden University who studies hallucinations and other perceptual phenomena. Most prior research consists of case studies, exploring the experiences of one patient at a time—this is the first study to examine the brains of a group of patients.

Friedrich points out that while he and his colleagues were successful at mapping brain networks that may be associated with the symptoms, they still want to understand exactly how these brain networks malfunction. For some patients, objects and bodies shrink—and for others, they enlarge.

A better understanding of Alice in Wonderland syndrome could demonstrate how perceptual disturbances lead to abnormal ideas about bodies more generally, Friedrich says, which has implications for understanding and treating anorexia or other body image disorders. There is some overlap in the brain areas that are overactive in people who have anorexia and Alice in Wonderland syndrome.

Friedrich says, “We should be a little cautious about our own perceptions and question our own perceptions, because sometimes they’re just not reality.”

—Katharine Gammon



ENVIRONMENT

Will Plants Grow on the Moon?

THREE HUMBLE PLANTS FROM EARTH will soon travel to a new home on the moon.

The plants—a mustard cress, a type of brassica, and a duckweed that grows in ponds—are part of the LEAF project and will be placed on the moon’s surface when NASA’s Artemis III mission arrives there in the near future—possibly as soon as 2026. The plants will be transported in a “growth chamber” containing air, heat, and internal lights, but they will be exposed to lunar gravity and most types of lunar radiation.

“What we are really looking at is the effects of lunar radiation on plant growth,” says Marshall Porterfield, a biological engineer at Purdue University and one of the scientists leading the LEAF experiment. Finding plants that grow best on the moon is a crucial aspect

of what space scientists call “bioregenerative” life support—the idea of sending not just humans but entire human ecosystems into space. Scientists want to figure out how to provide enough air, food, and water for astronauts on space missions that may take months or years, and biological solutions could help make that a more realistic goal.

The plants will take root in the growth chamber before the launch, and the project will measure how well they grow under lunar conditions. The moon has virtually no atmosphere and only a very weak magnetic field, so its surface is flooded by radiation from the sun and cosmic rays—about 200 times stronger than on Earth. Meanwhile, gravity on the moon is roughly one sixth as strong as that on Earth. When the astronauts leave after a week or so of exploration, the growth



chamber will be split in two. One half of the plants will return to Earth for study; the other half will stay on the moon.

One of the species—the mustard cress *Arabidopsis thaliana*—was chosen because it is a model organism that has been studied by biologists for decades. That detailed understanding will make it easier to decipher its response to the lunar environment. The brassica is an edible oilseed that was genetically bred to be fast-growing, which could be useful on the moon. The duckweed may be uniquely suited to space: It grows in water without roots, helps to filter the water it grows in, and contains many nutrients humans need to survive.

Porterfield was inspired to work on space travel by his early memories of the Apollo 11 journey to the moon in 1969, when he was just 3 years old. The LEAF project will be the culmination, so far, of his research into growing plants on the moon. He has already studied how the plants respond to the microgravity environment on the International Space Station. (Growing plants on the ISS is a complex business, and Porterfield says a chief concern is that plant roots depend on gravity to draw water.)

Porterfield will examine the genetic material returned to Earth from the experiment, which will reveal how the plants adapted during their sojourn—they're expected to create substances in their cells to protect them from increased radiation, for example. The plants that stay on the moon will be monitored by video, probably until they freeze to death in the two-week-long lunar night, he says. (Surface temperatures during the moon's long night have been measured at below -200 degrees Fahrenheit, near the freezing point of many gasses. The Artemis III astronauts won't stay for a lunar night, but future missions will need to find ways to keep warm.)

Porterfield wasn't involved in recent experimental attempts to grow plants in lunar regolith—the mix of rock chips and mineral fragments that covers the moon's surface—but he says learning how these plant species respond to real lunar conditions will be more important. For a start, it is unlikely that any plants will ever be grown in unprocessed lunar regolith, which lacks the essential chemicals and useful organic substances of soils on Earth.

The plants that stay on the moon will be monitored until they freeze to death.

“We’re not going to go up there and start planting plants on the moon,” Porterfield says. Instead, he says, the astronauts will use hydroponic systems, which can be lightweight and maximize the growth of plants by supplying them with nutrient-rich water in a specialized growth medium, rather than soil.

“This project and others like it will certainly be helpful in growing supplementary crops for astronauts on the moon,” says UCLA systems ecologist Jane Shevtsov, the co-founder of the Propagule Space Ecology Institute and an expert in bioregenerative life support systems who isn't involved in the LEAF experiment. The response of plants to microgravity on the International Space Station is known, but “we know ... almost nothing about how they and other organisms respond to partial gravity,” she says.

How they will respond to intense lunar radiation is perhaps the biggest question currently—the International Space Station orbits within the Earth's magnetic field, and so it is exposed to much lower radiation levels than the lunar surface. A similar experiment on a recent Chinese moon mission—the Chang'e 4 biosphere experiment—suffered an engineering failure and so lasted just nine days when it had been scheduled to run for 100. “The big challenge here is the engineering—making sure that LEAF doesn't suffer [that] kind of failure,” says Shevtsov.

If these three little plants can thrive on the moon in spite of the challenging conditions, they may make way for the lunar gardens and farms of the future.

—Tom Metcalfe

ZOOLOGY

Crows Are Even Smarter Than We Thought

CROWS AND RAVENS, which belong to the corvid family, are known for their high intelligence, playful natures, and strong personalities. They hold grudges against each other, do basic statistics, perform acrobatics, and even host funerals for deceased family members. But we keep learning new things about the savvy of these birds, and how widespread that savvy is among the corvid family.

Earlier this year, a team of researchers from Lomonosov Moscow State University in Russia and the University of Bristol found that a species of crow called the hooded crow—which has a gray bust and black tail and head feathers, making it look like it is wearing a “hood”—is able to manage a mental feat we once thought was unique to humans: to memorize the shape and size of an object after it is taken away—in this case a small piece of colored paper—and to reproduce one like it.

This kind of feat, according to animal behavior researchers, requires the ability to form “mental templates.” Essentially, a mental template is an image in the mind of what a particular object looks like, even when that object is not present. Mental templates allow animals to create tools, which can be used to get food or make a stronger nest, both ultimately leading to a better chance of survival. They might also make it possible for individuals to learn about tool making from other members of their species—and to pass along improvements in tool making over time, often called “cumulative culture,” which so far seems rare among non-human animals.

We have been looking for evidence that different corvid and other bird species can create mental templates since at least 2002. That year, researchers published findings showing that Betty, a captive New Caledonian crow, was able to spontaneously bend a piece of wire to create a hook that she could use to grab a hard-to-reach treat. Betty had successfully used a pre-made hook to obtain the treat in earlier trials but in follow-up tasks didn’t seem to fully understand how hooks work. The researchers decided she must have formed a mental template of the hook, which she then reproduced. So far, researchers have found that Goffin cockatoos,



a kind of parrot, can also create tools spontaneously, which could indicate similar mental agility.

But the new hooded crow findings suggest that the ability to learn this way could be more widespread than we thought, says Sarah Jelbert, a comparative psychologist who studies animal behavior at the University of Bristol and is one of the authors of the study. Creating and using mental templates might be a skill that evolved in the ancestor of all corvids, the Corvida branch of songbirds, or perhaps it is even shared more broadly across the animal kingdom, she says.

For their study, Jelbert and her colleagues first trained three hooded crows—Glaz (15 years old), Rodya (4 years old), and Joe (3 years old)—to recognize pieces of paper of different sizes and colors. To do this, they exposed the birds to “template” pieces of paper in different colors and sizes for several minutes before removing them—and then rewarded the birds for dropping scraps that matched these templates into a small slit.



The crows were next given the opportunity to manufacture versions of these objects in exchange for a reward. The researchers found that all three crows manufactured objects that matched the original template object they had been rewarded for in both color and size—even though the treats in this second stage of the experiment were awarded at random.

The researchers also observed that Glaz, the oldest of the three hooded crows, seemed to be the most proficient at making scraps that looked like the ones the bird was trained on. This finding suggested to them that mental templates may be linked to experience garnered with age.

“Unlike humans, who regularly copy each other’s behavior ... we don’t have much evidence that crows will watch each other and deliberately copy what another crow is doing,” Jelbert says. However, they will steal each other’s tools—in particular, juvenile crows often steal their parents’ tools when they are young. So it’s possible that young crows learn how to make different types of tools from experience stealing their parent’s tools, using them, remembering what these tools look like, and then trying to create something similar, Jelbert says.

What qualifies as a mental template, and how flexible these templates are, seems to be up for some debate. Research suggests birdsong and mating

Young crows learn how to make different types of tools by stealing their parent’s tools.

practices may rely on certain kinds of mental templates, which can backfire if a bird memorizes behavior from the wrong species. “For example, if a song sparrow gets imprinted on the song of a swamp sparrow and sings a song from a different species rather than its own, it will have difficulty finding mating partners,” explains Andreas Nieder, a professor of animal

psychology at the University of Tübingen and a lead researcher on corvid neuroscience, who was not involved in this study. “Similarly, if one finch species gets sexually imprinted on another, it may show courtship displays to the wrong species in adulthood.”

Nieder says this kind of imprinting can become fixed in the bird’s brain, and is not changeable even in new environments. “In this case, templates may no longer represent intelligence but rather the opposite,” he adds. Researchers have not yet determined whether mental templates related to tool making remain flexible, though there is some evidence in New Caledonian crows that they may evolve.

For biologists and comparative psychologists, understanding the ways corvids use mental templates can help to illuminate not just the nature of bird intelligence, but of intelligence across the animal kingdom and evolutionary time.

—Kenna Hughes-Castleberry

TECHNOLOGY

The March of the Mushroom Robots

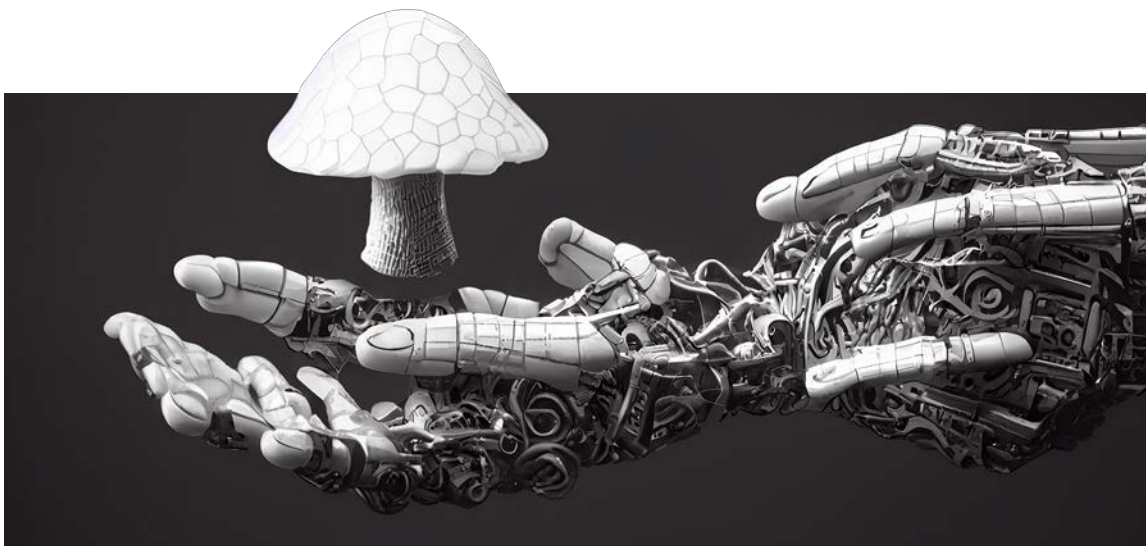
IMAGINE A CYBER-FUNGUS on the move, the soft sinuous flesh merged with synthetic parts, a kind of creeping chimera.

Recently, a team of scientists cobbled together two such hybrids: Powered by the fungi’s bioelectrical signaling, one walked and the other rode on wheels. Their findings were published in *Science Robotics*.

The work is part of a growing field called biohybrid robotics, which aims to make robots more lifelike by

fusing them with living tissue. “Mammalian tissue is hard to work with, but mushrooms are easy,” says Robert Shepherd, a mechanical and aerospace engineer at Cornell University and one of the authors of the paper.

Shepherd and his team experimented with king oyster mushrooms, which they cultivated themselves. The group started with the fruiting bodies—the mushroom caps we see above the soil—as the living material, but they soon learned that these caps decompose



too quickly. So they turned to mycelia, the root-like structure of a fungus consisting of a mass of branching filaments.

Mycelia have evolved to sense their environment, communicate over large distances, and transport nutrients. They are also naturally sensitive to light. It turns out this sensitivity can be used to power movement. The team created an electrical interface that interpreted the mycelia's activity and translated it into information to move the robot parts. When stimulated by ultraviolet light, the robot fungi fled from the light.

Unlike animal cells, fungi can be easily cultured in large quantities, and it is relatively simple to keep them alive: They tend to last for about a month before they start to decompose, says Shepherd. Some can also thrive in extreme environments, such as the Arctic and Antarctic, nuclear radiation sites, and highly acidic and saline conditions, which makes them great for robot hybrids that would operate in hazardous conditions.

Working with living tissues gives a bit of an existential flair to robotics. "Even though they are very durable, they do start to die," says Shepherd. "Anyone working in biohybrid systems has to deal with the life cycle: Robots get older, and their signals slowly get weaker."

Robert Katzschmann, a roboticist in the Soft Robotics Lab at ETH Zürich in Switzerland says the idea of using fungi to control a robot is innovative—though it comes with some challenges. "I'm not sure how far

we can take fungi for more complex roles in robotics," he says. But their sensitivity to environmental stimuli could make them very useful as sensors, he says, or in structural materials. "It'll be fascinating to see where this research leads," he says.

Shepherd thinks the applications fall in two broad categories: One is using mycelia to create a kind of circulatory system inside robots, one that would transmit energy from one component to another—"like a venous network ... inside a machine."

The other application is using these robots out in the world. Since mycelia are so adept at sensing the chemical and biology signals in their environment, for example, they could measure soil properties to help farmers determine the optimal amount of phosphorus, fertilizer, or pesticides needed to manage crops. Shepherd says mycelia have an advantage over existing technologies used to measure soil properties in that they are more sensitive to a wider range of biological and chemical threats and rewards and they are inexpensive to develop.

Working so closely with fungi has made Shepherd think about webs of connection—not unlike the massive webs of fungal filaments lying quietly below the surface of the Earth. "I am thinking more about how life is interconnected with everything," he says—even robots.

—Katharine Gammon



ZOOLOGY

This Tiny Frog Is Fierce

THE VERDANT RAINFORESTS of Costa Rica are home to many species of tiny glass frogs, named for their semi-transparent skin and translucent bellies, which can reveal their organs from underneath. The elusive amphibians pictured here, known commonly as La Palma glass frogs (*Hyalinobatrachium valerioi*), measure about three quarters of an inch and sport a mottled coat that mimics the lime-green coloration of their leafy surroundings. As arboreal and nocturnal frogs, La Palmas spend most of their lives hopping between trees and disappearing under leaves at night, perfectly camouflaged.

During the mating season, from May to late October, male glass frogs become increasingly territorial as they search for mates, emitting high-pitched squeaks, brays, and other calls to entice females and defend their space. This mating ritual is known as amplexus, Latin for “embrace.”

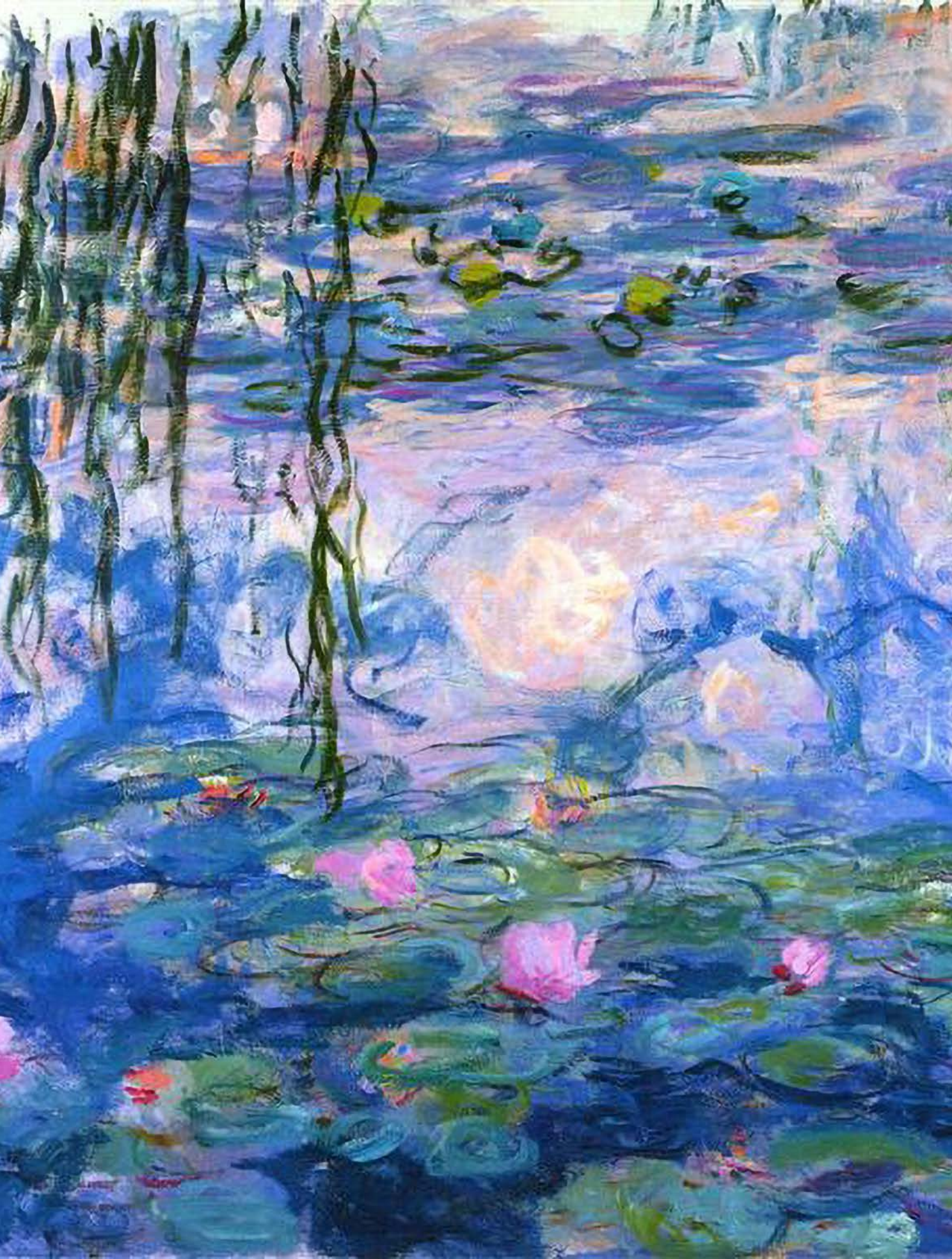
Photographer Emanuele Biggi captured a male La Palma glass frog mating with a female, grasping her in an intimate embrace and preparing to fertilize her eggs as she lays them. Males often mate with several females in the same location; egg clutches from previous matings sit near the pair on the same leaf. The act of consummation shown in this photo is rarely seen by humans, as these frogs usually lay their clutches in the dead of night and on the underside of leaves that dangle over streams and rivers.

—Liz Lindqwister

Photo by Emanuele Biggi

This story originally appeared in bioGraphic, an independent magazine about nature and regeneration powered by the California Academy of Sciences.





Your Memories Are Like Paintings

Why your brain interprets your past

BY KEVIN BERGER



LISTENED TO A FAVORITE ALBUM from 1983 the other day that gave me the profoundest joy. I danced around my kitchen singing along to every word. My whole body felt happy.

The album is *Field Day* by the rock singer and songwriter Marshall Crenshaw. Everything I love in rock is there—melodies that ingratiate, beats that elevate, and a voice ingrained with regret for love gone astray. “Do you remember the promise I gave you? The one I swore I would hold to?” he sings in the song “Our Town.” “Well, you’re there, I’m here, and everything I said was wrong.” The whole album is just perfect.

I hadn’t listened to *Field Day* in 25 years. And what I was feeling wasn’t nostalgia—longing for better days gone by. That’s because of Crenshaw’s natural elan as a songwriter. *Field Day* transcends the pop culture of the ’80s. Every note sounded as fresh as if it was written today.



I LOVE ROCK AND ROLL Little wonder that Charan Ranganath scores the neurobiology in his book, *Why We Remember*, with a rock-and-roll flourish. He plays guitar and sings in a rock band, Pavlov's Dogz, made up of fellow neuroscientists. That's neuropsychologist Brian Levine on sax.

Turns out memory is a castle made of sand. That's unsettling, no?

It's also because better days are a myth. Our brains never see the past clearly. They are like painters who are never satisfied. They constantly retouch the past with the colors of the present, putting a fresh version of ourselves on display for us to ponder.

That's one of the captivating insights in 2023's *Why We Remember* by Charan Ranganath, a professor of psychology and neuroscience at the University of California, Davis. Memories are not a true or false picture of the past; they are a Monet lily pond.

"Most paintings typically include some mixture of details that are faithful to the subject, details that are distorted or embellished, and inferences and interpretations that are neither absolutely true nor entirely false, but rather a reflection of the artist's perspective," Ranganath writes. "The same is true of memory."

I came away from *Why We Remember* with a beautiful picture of how memories make up the canvas of our mental lives. It's an unnerving picture, too. Memories are as sensitive as teenagers. The slightest change in mood or environment will cause them to unravel or change appearances.

"Our memories are dynamic, malleable, and sometimes inaccurate because our brains were designed to navigate a world that is constantly changing," Ranganath writes. "Human memory needed to be flexible and to adapt to context more than it needed to be static and photographically accurate."

That's a pretty great insight. It's also pretty great how Ranganath scores his neurobiology with a rock-and-roll flourish.

Our brains are not designed to give us the entirety of reality.

In his time away from directing the Memory and Plasticity Program at UC Davis, Ranganath plays guitar and sings in a rock band (made up of fellow neuroscientists) called Pavlov's Dogz. Their repertoire is mostly songs from the '70s and '80s by David Bowie, the Ramones, Joy Division, the Pixies, and Gang of Four.

Ranganath names chapters in *Why We Remember* after songs ("Just My Imagination," "More Than a Feeling") and opens them with quotes from Iggy Pop, the Flaming Lips, and this scientifically accurate slice of sageness by Nick Cave: "Memory is imagined; it is not real. Don't be ashamed of its need to create."

When Ranganath and I spoke over video recently, he was in his home office in Davis, sitting in front of a wall of guitars. I told him his book gave me an existential shiver. Our self, built on our memories, is our psychological anchor in a turbulent world. Turns out it's a castle made of sand. That's unsettling, no?

"Yes, it definitely can be," Ranganath said. "Although, it's not as if people who have amnesia have no sense of self. You can have a significant memory disorder and still have a sense of self. But it's incredibly impoverished. What you find in people who suffer memory loss from a stroke or electroconvulsive therapy is that their sense of self gets stuck at the time of the event. They have an idea of who they were but can't update it into a sense of who they are now. It can be true for all of us. As I get older, it can be scary to look in the mirror. I think, 'I should be looking differently than I do!' So, in some sense, we don't optimally update our memories to catch up to our current selves."

Evolution is to blame for our shaky memories and selves. If we evolved to remember everything, we couldn't function due to the overload of sensory information. We'd be mentally paralyzed on the savanna. While we stood there recording every sensation—the whoosh of the wind, the

metallic gleam of the dragonfly, the musty smell of the air—we'd become an easy lunch for a predator. So much for human survival.

Instead, the clever brain uses its energy wisely to store only the sensory inputs that matter—the ones that seem new, surprising, have an edge. “Our brains are designed to give us the most information with the least amount of resources,” Ranganath told me. “That allows us to be cognitively nimble and flexible, with very little energy consumption. There’s no free lunch in a biological system like memory.”

Enter another clever invention of evolution: emotions. Fear, lust, despair, love, a whole suite of sensations, stir up biochemicals like nor-adrenaline and dopamine that flood the brain to stabilize or modulate the assemblies. The more intense the emotion, the more likely we are to remember the experience that caused it. Our ancestors quickly learned not to sleep near the leopard den again.

How the brain creates “episodic memories” is a focus of Ranganath’s research. Neuroscientists have identified two basic types of memory. Semantic memory refers to remembering facts like the capital of New Jersey. Episodic memory refers to the act of recall that time-travels into the past to revive the experience of first hearing Bruce Springsteen’s “Thunder Road.”

Ranganath and his collaborators have done experiments that highlight how the brain stores information in schemas, or diagrams. “The way the human brain uses schemas to construct new memories is not unlike how an architect uses a blueprint to design houses,” Ranganath writes. “An architectural blueprint functions as a kind of map of the barebones information about the structure (walls, doors, stairs, windows, and so forth) that shows how everything is connected. The abstract nature of a blueprint means it can be reused over and over.”

The default mode network, an area in the neocortex, stores the schemas in cellular pieces that can be used to assemble new memories. The hippocampus, the seahorse-shaped area in the middle of the brain, is the builder.

PLAY IT AGAIN

Why does the music you love when you were young remain your favorite throughout your life? That doesn’t apply to everybody, of course. But social scientists tell us it applies to most.

According to a 2022 survey of Americans, aged 18 to 84, music released when you are a teenager tops your personal charts. New music released after you turn 35 rates thumbs-down, regardless of when you were born.

The survey was done by a savvy group of Australian consumer-behavior researchers, one of whom, Carl Driesener, told *Washington Post* data columnist Andrew Van Dam the results were redolent of the academic concept “declinism.”

“Declinists believe the world keeps getting worse,” Van Dam explains. “It’s often the natural result of rosy retrospection, or the idea that everything ... looks better in memory than it did at the time. This may happen in part because remembering the good bits of the past can help us through difficult times.”

Quite right, say neuroscientists who study memory. When anxiety and uncertainty won’t leave you alone, your favorite music comes to your emotional rescue.

“When we look back at the past, we tend to focus on a specific period of our lives, between the ages of 10 and 30,” writes Charan Ranganath in *Why We Remember*. “Something about listening to a song or watching a movie from those formative years can give us a sense of meaning, connecting us to an idealized sense of who we are.”

That something is an emotional charge that grants the music from your formative years a stable home in your brain.

Continued on page 28



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“Emotionally arousing experiences are associated with the release of neuromodulators that stabilize memory, so they’re more resilient over time,” Ranganath says. “Also, when we recall those experiences, we reactivate the cell assemblies formed by them. In fact, the emotional intensity of retrieving the memory often brings a feeling of vividness over and above the initial experience, whose details have faded.”

If one thing defines being young, it’s emotionally arousing experiences. Your brain is in an “incandescent frenzy” when you’re a teenager, says neuroscientist and primatologist Robert Sapolsky. Your prefrontal cortex—“which does all that mature, adult, sensible stuff, like long-term planning, impulse control, emotion regulation”—is simply not formed yet. However, other brain areas, notably the limbic system, key to emotions, are “going full blast.”

Here’s what happens in your young brain, Sapolsky explains with his characteristic exuberance. Without a fully formed prefrontal cortex, neurochemicals like dopamine that stimulate pleasure have the run of the place. Frenetic emotions supercharge every novel thing you discover, especially music.

“When you’re in your first window of developing your own tastes, the most important thing in the world is for you to communicate to the universe how different you are from any generation that came before you,” Sapolsky says. “So, some young misanthrope shows up and invents some new cultural style, and the next thing you know you’ve got a Jimi Hendrix. A whole generation identifies with him and 30 years later they’re sitting there and saying, ‘Well, if this music was good enough for when we were sleeping together at Woodstock, it’s certainly still good enough now, and forget whatever garbage these 18-year-olds are listening to; I know what’s good music.’”

In the brain, the hippocampus has great connections. “It gets inputs from virtually every kind of motivational chemical in the brain you can imagine,” Ranganath explained. During the act of remembering, the hippocampus uses its connections to the default mode network to “put the pieces together to store a specific episodic memory.”

Ranganath, fond of metaphors, writes that his and his collaborators’ research reveals forming an episodic memory is like building with LEGOs. “With LEGOs, you can use an instruction sheet to rebuild [a] medieval scene or use a different set of instructions that show how the same bricks can be combined to reenact a scene from *Star Wars*. Likewise, when it comes to memory, the [default mode network] has pieces that can be reused across many different events.”

In the brain, though, the pieces don’t hold together snugly. “The very act of recalling a memory can lead it to become fragile and changeable,” Ranganath told me. “It can lead to distortions and misinformation, to the point where the memory becomes corrupted.”

The problem is other neurochemical players are always anxious to add their own pieces to a memory. These spoilsports are the cell assemblies that animate our present states of mind and moods. The act of remembering, Ranganath said, is “dominated by the beliefs and perspective we have in the moment.”

Our present perspectives often choose the movie to play in our minds. When the world looks ugly, it’s often nostalgia, “that bitter-sweet feeling of joy and sadness,” Ranganath said, that comes to our emotional rescue. We imagine carefree days of smart leaders and safe communities, friendly neighbors and better music. It’s perfectly natural.

“People tend to have a positive memory bias, and tend to recall positive events more often than negative ones,” Ranganath said. “And they tend to recall them more positively than they actually were. Then there’s the flip-side, which is when you’re in a negative mood,



you tend to remember events more negatively than they actually were. Every demagogue you can think of has cashed in on nostalgia, used it to create a toxic worldview of society falling apart, saying ‘I’m the one to take us back to the way things were.’”

Given the chameleon nature of our memories, changing their colors to suit different environments, do we ever see anything for what it is, remember it for what it was? To borrow one of Ranganath’s rock lyric references, *Is this the real life? Is this just fantasy?*

“Our senses, our brains, are not designed to give us the entirety of reality,” he said. “They’re a window into reality. That’s good because reality is so infinitely dimensional. As we were discussing, you couldn’t function if you sensed everything. My dog can sense all sorts of frequencies that I can’t. So, we’re only getting a narrow band of the world, anyway.”

Yet we must have some clear recollections of events that happened to us: “We do,” Ranganath said. “Our memories clearly have elements of reality. In our lab conditions, we find some people are extraordinarily precise in their memories. They can remember all sorts of details. But the thing is, we infuse those details with meaning, with perspective, and build these stories, and that is uniquely human.”

Memory, in fact, is an act of imagination. Mounds of research, based on brain scans, show the same mental processes and areas of the brain that we use to fantasize about sipping exotic cocktails in a hammock on a tropical beach, are the same processes we draw upon when recollecting the time we were, well, sipping exotic cocktails on a tropical beach.

“There’s a deep link between memory and imagination on so many levels,” Ranganath said to me, excitedly. “One of the cool levels to think about today is the products of human imagination are truly innovative, as opposed to something that I might get out of ChatGPT from some clever prompt. That’s because we have such weird experiences that are totally unique. We are predisposed to being in different places

That’s the music deep-seated in your brain talking. And that’s not a metaphor. Memories are seated in certain brain areas in individual components, Ranganath says. The act of remembering is your brain at work reconstructing the components that best suit a current situation. Your brain has only so much energy to work with, so it selects only the components that aid how to behave in the moment. The human brain is “remarkably energy-efficient,” Ranganath says.

Further, writes neuroscientist Daniel Levitin, an expert in music and the brain, in his new book, *I Heard There Was a Secret Chord: Music as Medicine*, “the components of music hold a privileged position: They tend to be more accurate than other memories, even for nonmusicians.” Why the privileged position for music? “In general, it is easier to remember information when there is some sort of organization scheme inherent in the material,” Levitin writes. “Music—even more so than language—is a highly structured medium, meaning that the structure itself can help to scaffold one’s memories.”

Ranganath, who is also a musician and plays in a rock band that covers songs from the ’70s and ’80s, says he knows he should seek out new music. But as he gets older, he says, the past won’t release its pull. “I confess, the more music I carry with me, the harder it is to get into new music. I am weighed down by all the music I used to listen to and love.”

—Kevin Berger



Remembering is dominated by the perspective we have in the moment.

to experience different things, talking to different kinds of people, to feeling the full range of human emotions. We can put together things that would never come through some large language model trained on the internet.”

Interestingly, Ranganath compared the process of memory to being a scientist. His main gig, he said, was to collect data from experiments. He followed best practices to ensure his data was as accurate and unbiased as possible. But the theories hatched from science always came down to interpretation. “Interpretations are meaning generated from data,” he said. “The key is we don’t often bother to look at the difference between our interpretations and the data.”

The same is true for memory. We often don’t look at the difference between our experiences and our brain’s interpretation of them. But understanding that memories are a mix-and-match process, designed to be nimble and flexible to adapt to changing circumstances, can transform us. We can reflect on ourselves in ways that expand and animate our perspectives today.

This may not be a revelation to turn-of-the-20th-century French writer Marcel Proust, whose reflections on his memories constitute one of the greatest works of art in history, his series of novels, *In Search of Lost Time*. For the rest of us, to understand that your memories are not photographs but paintings that your brain, being the imaginative artist that it is, is constantly retouching, is a beautiful thing.

Listening to *Field Day* recently didn’t transform my brain into a movie of my life in 1983. But it certainly did stir neurochemicals to create traces of myself and my feelings from that year.

A vivid scene in my mind was my tiny living room in my San Francisco cottage, where I had my stereo, and often played *Field Day*—the vinyl LP, of course—as a release from the stress of finishing my master’s thesis in English literature. I wrote about how Southern author Walker Percy put the existentialist thinkers to work in his comic and ironic fiction about alienation.

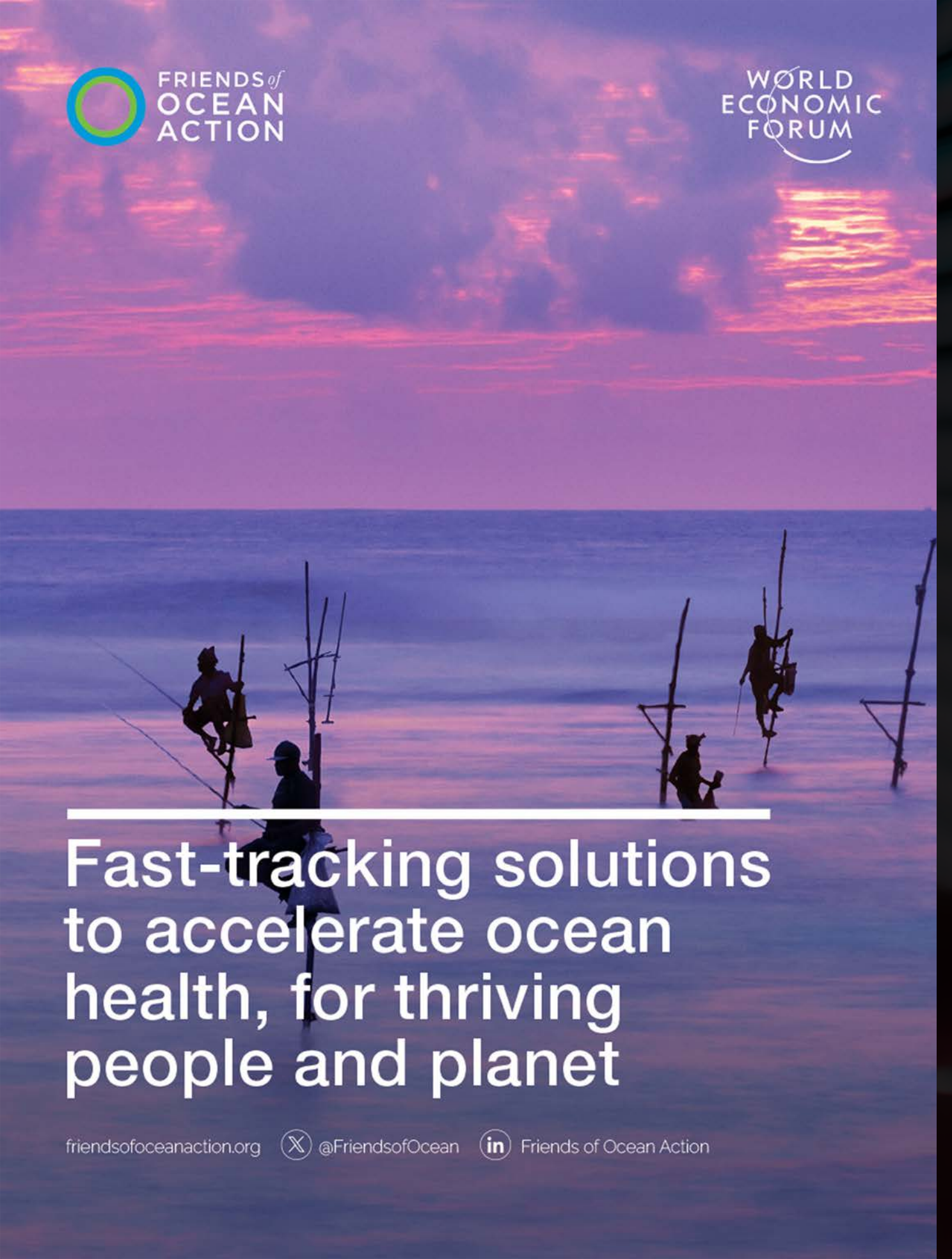
Actually, my most detailed recollection of that time was carrying my pale blue electric Smith Corona to the typewriter shop on Market Street to get the eraser shavings cleaned out of it and one of the keys unstuck. “It’s time to replace this thing,” the owner said to me.

Those are wonderful recollections because I loved writing my thesis and was happy and proud with how it turned out. But playing *Field Day* in 2024 was more meaningful than it was in 1983. My listening mind had gained 41 years of experiences and memories. I thought about the deep and important place of music in my life, carrying me through amazing and wrenching times. My past was present, and I felt totally alive.

After his decades of research, I asked Ranganath what memory taught him most about being human.

“I was really impacted by Daniel Kahneman’s observation that we have an ‘experiencing self’ and a ‘remembering self,’” he said. “Your experiences of things are continuous in real time and associated with all sorts of feelings and thoughts and sensations. And then in the cold light of reason you have this remembering self in a completely different context, trying to make sense of yourself, a person with a very narrow window of experience. I tried to embrace that and very consciously ask myself, especially after I turned 50, ‘What are the memories I’m going to carry with me from this point on?’ I want to make choices to get the best memories I can.” 🌀

KEVIN BERGER is the editor at large at *Nautilus*.



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The Odds That Aliens Exist Just Got Worse

How geology resolves the Fermi paradox

BY MARCIA BJORNERUD

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HE QUESTION OF WHETHER HUMANITY is alone in the cosmos creates strange bedfellows. It attracts astronomers and abduction conspiracy theorists, pseudo-archaeology enthusiasts and physicists. And loads of science-fiction writers, of course, who have conjured extraterrestrials from Klaatu to Doctor Who. Douglas Adams imagined a galaxy so full of life that its interstellar travelers needed a hitchhiker's guide.



Given the diversity of voices that have weighed in on the possibility that other civilizations may be out there, it is surprising that few geoscientists—people who study the one planet known to host life—have weighed in on the cosmic conundrum. Physicist Enrico Fermi’s famous question, “Where is everybody?” has long lacked a geological perspective.

That’s what Earth scientists Robert Stern and Taras Gerya offer in a paper published in *Scientific Reports*. Earlier speculations about extraterrestrial civilizations were based primarily on astronomical and technological considerations like the number of planetary systems in the galaxy and how long it might take an intelligent species to discover and begin using radio waves. That left little attention for the specific attributes of potential host planets—other than the presence or absence of water.

Stern is a geologist at the University of Texas at Dallas who studies the evolution of the continental crust, and Gerya is a geophysicist at the Swiss Federal Institute of Technology who models Earth’s internal processes. Their conclusion may disappoint extraterrestrial enthusiasts: The likelihood that other technologically sophisticated societies exist is smaller than previously thought, because basic amenities we take for granted on Earth—continents, oceans, and plate tectonics—are cosmically rare.

How can we estimate the number of alien civilizations that might exist? In the early 1960s, the radio astronomer Frank Drake conceived of an equation that many researchers still use to gauge how prevalent advanced extraterrestrial societies might be. Although the term “equation” suggests a certain level of precision, the Drake formulation is really no more than a

Basic amenities we take for granted on Earth—continents, oceans, and plate tectonics—are cosmically rare.

crude, back-of-the-envelope guess at how many planets might conceivably host complex life—and have some possibility of communicating with us. Drake was optimistic about the possibility of interstellar communication: He later worked with Carl Sagan in developing the “Golden Record,” a gold-plated disc with information about Earth and human cultures that was launched in 1977 on a deep space journey aboard the Voyager I and II spacecrafts.

In the original equation, the estimated number of civilizations is a simple product of seven factors, or probabilities, multiplied together. Scientists have a fairly good handle on the first three of these for the Milky Way. There’s the rate of star formation in our galaxy; the fraction of those that have planets (probably most, given the burgeoning census of known exoplanets); and the average number of potentially habitable planets around such stars (based on how many would be sitting in the star’s “habitable zone,” the sweet spot where water can remain liquid).

The other four factors in the Drake equation grow successively more speculative. These are: the fraction of potentially habitable planets on which life likely has emerged (a variable that’s completely unconstrained, since only one case—ours—is known); the fraction of those planets on which intelligent life has developed (a criterion that often elicits dark humor about whether human life qualifies); the fraction of *that* fraction that have sent signals into deep space (again, just one known example, outgoing calls only); and the length of time those civilizations have been sending such signals (to be determined).

The plus or minus values on the final product resulting from this formula are gigantic, and the “solution” to the Drake equation has been determined to be between

1,000 and 100 million advanced civilizations in our galaxy (not 42, as Douglas Adams fans might have expected). While the size of this range is quite absurd, even the lower-end estimate of 1,000 suggests that we should have heard from someone by now. The fact that we haven’t encountered anyone is known as the “Fermi paradox.”

Bringing a geologic perspective to the problem, Stern and Gerya propose to resolve the paradox by adding two more factors to the already unwieldy Drake equation: the fraction of habitable planets with distinct continents and oceans; and the fraction of those planets with a plate tectonic system that has operated for at least 500 million years. The values of these terms are *very* small, they argue, because the development of distinct landmasses and water bodies, and the tectonic habit of crustal recycling—characteristics of Earth that we take for granted—are unlikely outcomes in the evolution of rocky planets.

With these new factors, the number of advanced civilizations in our galaxy that might communicate with us falls to ... almost zero.

This seems plausible, given the grand sweep of Earth history: Although life had emerged and diversified by at least 3.5 billion years ago, it remained mainly unicellular until about 560 million years ago, when macroscopic marine organisms first appeared. It took another 100 million years before plants and animals began to move onto land, and a further 450 million for tool-making humans to show up. And we’ve only been transmitting signals for about 50 years.

Stern and Gerya assert that while “life must evolve in the sea, advanced communicative civilizations must evolve on dry land.” This is because landscapes are more varied than seascapes, and therefore foster more evolutionary innovation, giving rise to creatures with more sophisticated sensory organs. This generalization may be true, but like so many other astrobiological hypotheses, it is limited by the fact that we have only one planetary example.

There could be other paths to technologically advanced life. The enormous diversity of marine organisms here on Earth, both in the fossil record and the modern oceans, is a reminder that there has been plenty of evolutionary experimentation in the seas over time. Plus, some recent origin-of-life theories suggest that

the first living cells popped up in land-based hot springs, not marine environments. Still, we are faced with our own facts: that the existence of distinct continents and oceans on Earth has engendered great biodiversity and that the one species to develop advanced technology is a landlubber.

Most geologists will agree with Stern and Gerya's argument that plate tectonics should be included as a criterion for long-term planetary habitability. Earth's tectonic system allows the planet's atmosphere and hydrosphere to remain in communication with its interior, in a remarkable, self-perpetuating cycle. Subducted ocean crust—seafloor that slips down into Earth's interior—carries water back into the mantle, and at shallow depths, this water lowers the melting temperature of mantle rock, giving rise to unusual magmas that create the continental crust—what we surface dwellers live on—which is rich in rare elements, like phosphorus, that are critical to life.

At greater depths, subducted water acts to decrease the viscosity of the mantle, allowing it to churn, or convect, more vigorously—which in turn drives plate motion. When the Earth's mantle exports heat via convection, it encourages the liquid iron outer core to convect as well, and this generates Earth's protective magnetic field, which shields the surface environment from harmful cosmic radiation. Without plate tectonics, continents would quickly be eroded to sea level. But tectonic collisions continuously rejuvenate Earth's topography, providing rivers with more energy to transport nutrient-rich sediments to shallow marine environments. In other words, plate tectonics is entangled with all the phenomena that support life on Earth.

A plate tectonic system like Earth's requires a very specific thermal combination of a cool, crisp outer shell, broken into movable pieces, and a warm, gooey underlying mantle capable of flowing in the solid state. Exactly when Earth achieved this balance is unknown. Since Venus and Mars show no evidence of subduction, it is unlikely that the early Earth had a full-fledged plate tectonic system from the start.

*Plate tectonics
should be included
as a criterion
for planetary
habitability.*

Stern and Gerya are well known in the geological community for arguing for a comparatively late start to Earth's plate tectonics—at the end of the Proterozoic Eon about 550 million years ago. In their view, diagnostic “plate tectonic indicators,” such as evidence for seafloor spreading and subduction, do not appear in the geologic

record before that time, and they posit that until then Earth had a Mars-like “single-lid” tectonic system. They use their paper to further advance this less common viewpoint, arguing that the emergence of multicellular life at that time was triggered by the beginning of modern-style tectonics, which would have accelerated delivery of critical nutrients like phosphorus to the oceans, leading to phytoplankton blooms that sequestered carbon and increased atmospheric oxygen levels.

But the mainstream consensus among geologists is that Earth had adopted its modern plate tectonic habits by at least 2.5 billion years ago—much earlier than Stern and Gerya contend. Starting around this time, ancient mountain belts (which survive as eroded remnants) began to have the same internal “architecture” as more recent ranges like the Rockies and Alps, and some of these belts preserve high-pressure metamorphic rocks diagnostic of subduction.

Regardless of when our planet's plates fractured and began moving, Stern and Gerya's paper makes a compelling case that planets anything like Earth are exceedingly scarce in the cosmos. That message should give pause to anyone who imagines that we might “terraform” another planet in a matter of a few human generations.

Does it really matter that the probability of receiving a communiqué from deep space has just become a little slimmer? It might turn out to be a good thing if it causes us to look down with new reverence at the beautiful, bountiful, mysterious planet right under our feet. ☺

MARCIA BJØRNERUD is a professor of geosciences at Lawrence University and the author of *Timefulness: How Thinking Like a Geologist Can Help Save the World*. Her newest book is *Turning to Stone: Discovering the Subtle Wisdom of Rocks*.

Excavating a Language at the End of the World

*How an old dictionary is revealing new perspectives
on an Indigenous culture*

BY KATARINA ZIMMER



DEEP IN THE SOUTHERN HEMISPHERE, where frigid waves lap against the toe of the South American continent, the sea has no single name. Locals have called it *tāralömbi* when the water is perfectly calm. *Čilamaii* are the swells that gather along the coast, *mötälömön* is the roughening of the water by western breezes. *Döna* is the term when certain winds ruffle the ocean's surface in such a way that the movement of fish underneath cannot be discerned and canoes must return ashore.

The Indigenous Yaghan people who have spoken these words are native to Tierra del Fuego—the mosaic of islands, fjords, channels, bays, and coves created by the submerged foot of the Andean mountains in southern Argentina and Chile. The Yaghan and their ancestors are thought to have persisted in this harsh, windy, and cold seascape for thousands of years. There, they have built canoes, from which they hunted sea lions and seals with harpoons. They have caught fish, gathered mussels, made ornaments, and celebrated rites of passage. They have roamed far and wide.

The last truly native speaker of Yaghan, Cristina Calderón, died in 2022. Up to a few hundred members of the group are still alive today—including Calderón's granddaughter Cristina Zárraga and others who are working to revitalize the language; Yaghan is classified as “dormant” by the Endangered Languages Project.

Although archaeologists have long been fascinated by the deep history of this seafaring, nomadic people, many of the physical remains their ancestors left behind have been lost to time. Fortunately, they have also left clues in the Yaghan language.

The Yaghan words for the sea were exhumed from a 19th-century Yaghan-English dictionary compiled in the late 1800s by an Anglican missionary. In a paper in the *International Journal of Historical Archaeology*, a team of Norwegian scholars argue that studying this historical snapshot of Yaghan could yield important clues about these people's lives over the centuries. The same approach could be used for potentially hundreds of other languages, dead, alive, or dormant, across the globe to better understand old ways of life, ancient ecologies, and humans' connection to the landscape.

Dictionaries, such as the one created for the Yaghan language, it turns out, can be excavated for rich and nuanced information missing from the physical archaeological record.

"You could think about language in a similar way as we think about the archaeological sites in a landscape," says the lead author of the new research, archaeologist

GRANDMOTHER TONGUE Cristina Calderón, pictured here, was the last known truly native speaker of Yaghan. She died in 2022, but her granddaughter Cristina Zárraga and others are working to revitalize the language. Historical perspectives, like that from the newly analyzed dictionary, help enrich contemporary understanding of the culture's deep history—and connection with the landscape of Tierra del Fuego.



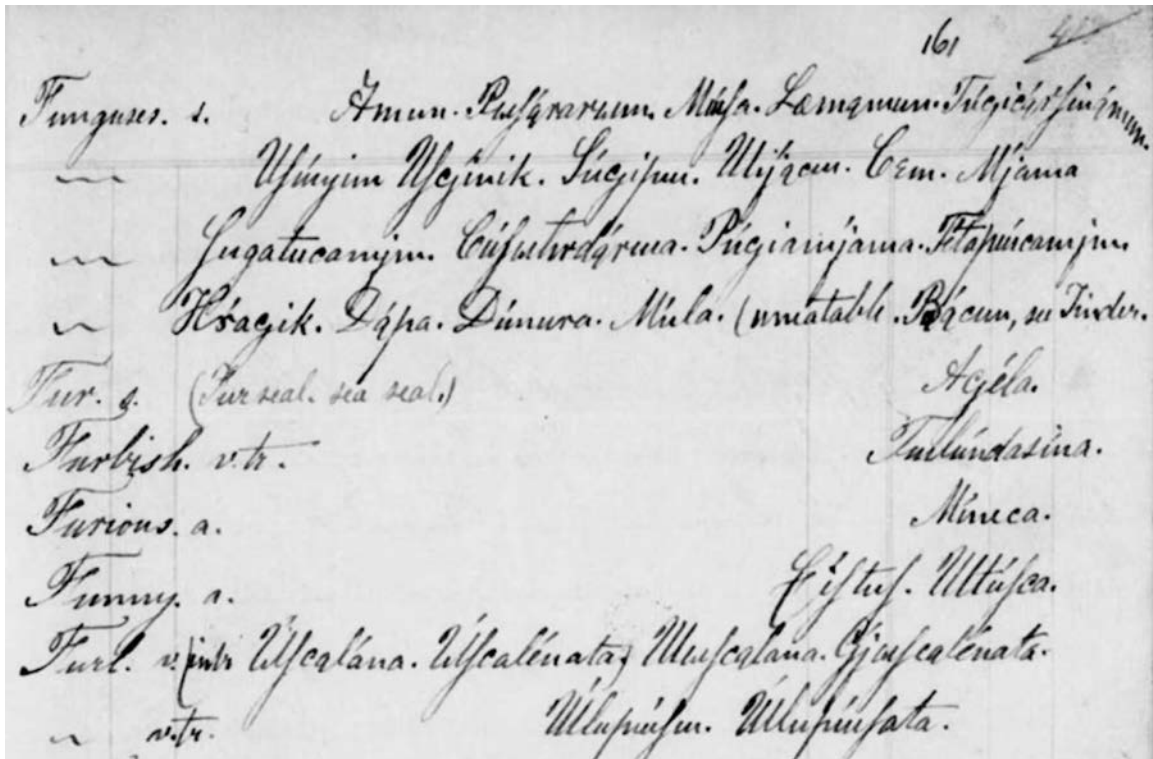
VÍCTOR ALEJANDRO CORREA RUEDA / WIKIMEDIA COMMONS

Dictionaries, it turns out, can be excavated for rich information missing from the archaeological record.

Jo Sindre Eidshaug of the Norwegian University of Science and Technology's Marine Ventures project, an international archaeological research effort. Eidshaug views language as something that "settles" a landscape just like physical artifacts, as people develop knowledge and vocabulary in places where they spent most of their time.

"This kind of research gives us a new tool to understand some [questions about] the life of these people in the past," adds Angélica Tivoli, an archaeologist at the Austral Center for Scientific Research of the National Scientific and Technical Research Council in Ushuaia, Argentina, who wasn't involved in the new work.

TODAY, WHILE LANGUAGE REVITALIZATION efforts of Zárraga and others are underway, little Yaghan is currently spoken in Tierra del Fuego. The Yaghan culture and language underwent a devastating decline after Europeans arrived. In the 1880s, about 90 percent of the Yaghan people died from infectious diseases Europeans brought. The decline continued into the 20th century, when many Yaghans continued to die prematurely and faced discrimination for speaking the language. Today's Yaghan people still fashion traditional harpoon points of whale bone and weave baskets, nowadays mostly to sell to tourists, but they can no longer canoe or boat freely due to restrictions by the Chilean Navy.



BY ANY OTHER NAME While trying to better understand the Yaghan language and culture—in order to craft translated Bible verse—a 19th-century Anglican missionary ended up creating a detailed map of the Indigenous group's local knowledge and worldviews within his handwritten dictionary. Here, he documented the many Yaghan words for fungi.

Thomas Bridges, who constructed the dictionary, first met the Yaghans as a teenager in 1856 and later lived with them for 30 years. Carefully documenting their language and culture helped Bridges to translate the Gospel of Luke into Yaghan, as part of Anglican missionary tradition to make the Bible accessible in local languages. But while a complete Yaghan Bible may never have come to fruition, Bridges' dictionary includes about 32,000 words. "That level of detail he was documenting—it's so beautiful," says Oxford University ornithologist Andrew Gosler, research director of the Ethno-Ornithology World Atlas which collects Indigenous knowledge on birds. "To be able to document that kind of detail," he says, demonstrates a closeness with the native speakers.

Most physical traces of Yaghan culture, like any remnants of foraged feasts, were lost to time.

Because Bridges was merely striving to record the Yaghan vocabulary as comprehensively as possible, his dictionary may be less colored by prejudices and personal agendas than ethnographic reports of the Yaghan by other missionaries and travelers, Eidshaug says. But still, the dictionary is limited in the kinds of questions about the past it can answer. Languages change over time, so it's unlikely, for example, to shed light on deep archaeological questions, such as the origins of the first marine hunter-gatherers in Tierra del Fuego some 7,000 years ago. Or to necessarily give a full picture of the richness and breadth of Yaghan life.

In other places, like Australia, male linguists have been historically more likely to ask men than women about their practices, documenting little on activities traditionally carried out by women, notes linguist Luisa Miceli of the University of Western Australia. Bridges also mostly worked with only one Yaghan couple—Okokko and Camilenna—to understand the language, possibly limiting his view of the communities' activities as a whole, Gosler says. And, many concepts in Yaghan are so specific to culture and place that they're hard, if not impossible, to fully encapsulate in other languages, adds Zárraga, who learned the language as an adult from her grandmother.

But the dictionary might have encoded detailed knowledge about the kinds of resources, practices, and deep environmental understanding that were assembled over hundreds or thousands of years in Tierra del Fuego, much of which hasn't been preserved in the archaeological record. "The kind of environmental knowledge that is picked up in this language has an antiquity to it," Eidshaug says.



WATERTIGHT INSIGHTS Many of the physical artifacts of the Yaghan people—whose ancestors have occupied Tierra del Fuego likely for thousands of years—have been lost to time and harsh weather. By digging through the 19th-century dictionary, scholars were able to learn more about the details of how people once made the canoes that plied the area’s waters.

Wherever they went, Yaghans accumulated knowledge and vocabulary about their environment—the climate, the sea and its inhabitants, the coastline, the beach, and the forested hinterlands of Tierra del Fuego. Archaeological studies have mostly focused on shell middens along the coast—ring-shaped piles of shells that were discarded around dwellings—where animal bones and bone tools were preserved thanks to the alkaline chemistry of the shells.

The dictionary catalogs commonly hunted and foraged foods that don’t preserve—fast-degrading things like crab shells, berries, and fungi—in line with some ethnographic reports. Eidshaug counted 48 Yaghan terms for

COURTESY OF SPRINGER LINK

The dictionary also offers a window into some of the intangibles of Yaghan culture and worldview.

local fungi, many that describe their ripening in rich detail. For example, *auačix*, the round yellow summer fungus that grows on the *šöšči* tree; *čikidönara* describes immature fungi; *pöša* the second stage just before the fungus opens in holes and gets puffy; and *dönara* is when they are fully ripe, shortly after falling from the trees.

Most physical traces of the central vehicle of Yaghan culture, the bark canoe, like any remnants of *auačix* feasts, were also lost to time. Yet the dictionary describes in detail the resources and strategies involved in canoe-making. Bark is cut from the *šöšči* tree, and wood fiber called *uri* is used for sewing. *Hušun*—seed stalks of wild celery—are sewn as pads into the seams to make them waterproof. *Tstägi* soil is used to cement the seams. *Tatega*—pieces of young smooth bark—are attached to the canoe’s upper edges to protect paddlers from blisters. Through words like these, “we get a broader picture of the material culture,” Eidshaug says.

The dictionary also offers a window into some of the intangibles of Yaghan culture and worldview. Some entries pertain to rituals, such as *kīna*, an initiation ceremony for boys aged 12 to 17. The Yaghan word “to go” is often combined with prefixes to indicate direction; some denote the cardinal directions like north and south, but others indicate “toward land” or “away from shore,” illustrating how people mentally divided their landscape. Other entries explain how Yaghans kept time according to the seasonal changes in nature around them. *Čgaiangūta* is the season for ripe *auačix* fungus. *Čtyägörana* is the season when *šöšči* tree bark loosens, *hākūa* for making spring canoes. *Iūan* is the time when older crabs carry the younger ones, *čiiūaiella* the time after they’ve separated.

The hope is that such investigations not only answer archaeological curiosities but also help the living communities engage more deeply with their past.

Information buried in the dictionary might also help interpret the physical archaeological record. In the dictionary, for instance, *uštānim* is described as a porpoise jaw used as a comb. *Isōska* is the lower jaw bone of a whale used as spear bones. Dictionary entries of this type could help archaeologists make sense of a hodgepodge of bones found underneath shell middens, and perhaps provide important context to certain tools, Tivoli says. “Maybe it’s a way of calling our attention to look deeper into the archaeological record,” she says.

Many nouns describe local animals, which represent a third of the dictionary. The wealth of different terms for certain animals—such as for shellfish—may reflect a recent increase in their importance as a resource relative to other creatures.

THIS NEW, LINGUISTIC APPROACH to uncovering more about a long-lived culture as described in Eidshaug’s paper is quite valuable, says archaeologist Flavia Morello of Chile’s Institute of Patagonia and the Cape Horn International Center, both part of the University of Magallanes. It shows how dictionaries can act as gateways to unique cultures and in doing so help foster a deeper societal appreciation for cultural diversity and the kinds of relationships humans can cultivate with landscapes. “It’s very inspiring as a paper,” she says.

Archaeologists elsewhere are increasingly interested in leveraging language in similar ways. Miceli and her colleagues recently published a pilot study to explore what kind of information they could glean—from dictionaries of 10 Aboriginal languages in Australia—about domestic fire use, and whether this could be useful in guiding archaeologists in excavating sites, Miceli says. Past collaborations between archaeologists and linguists have often centered on answering questions about the likely homeland of ancestral languages, and how and why they spread, rather than using vocabulary to help with archaeological excavations. “That, I think, is quite new,” Miceli says.

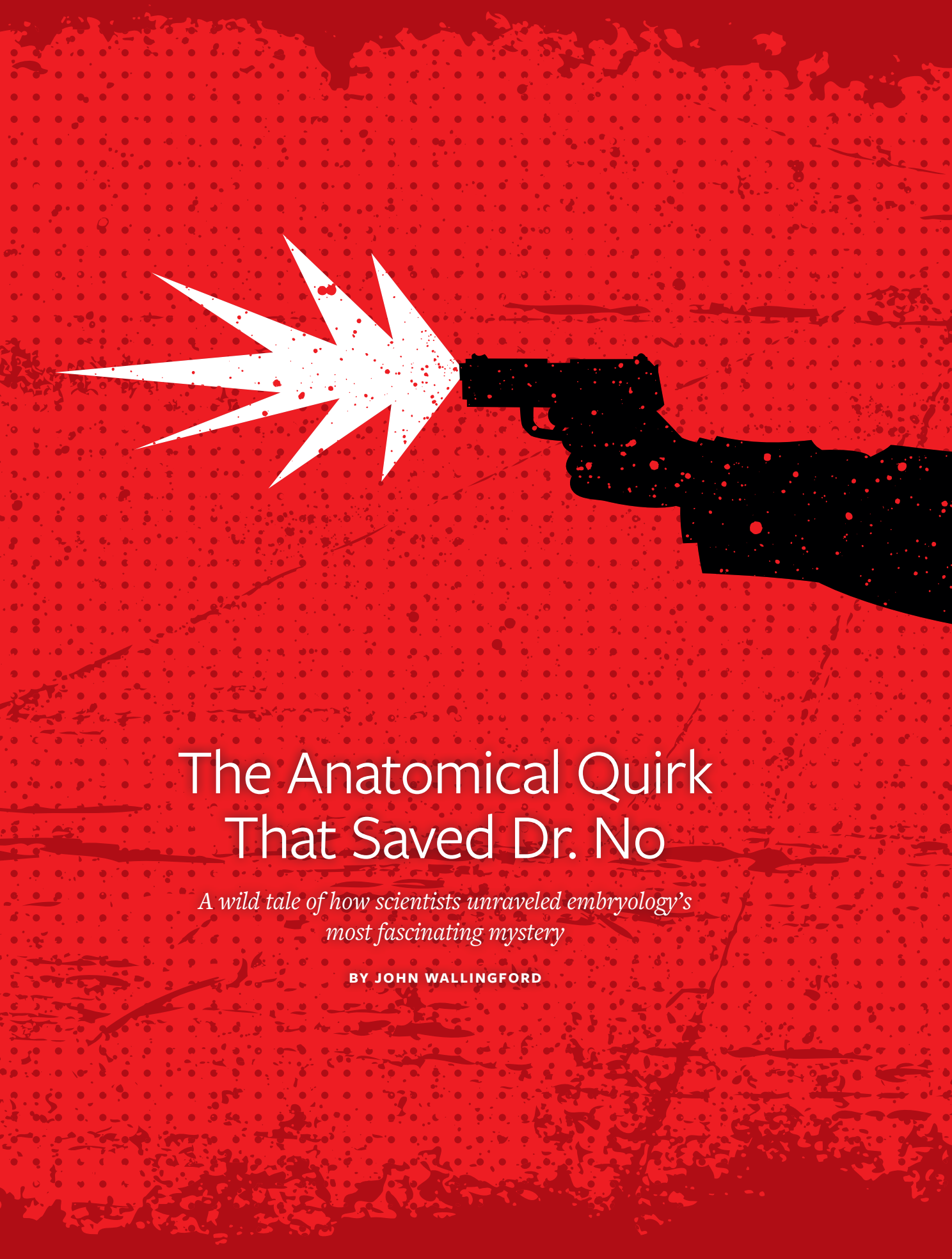
Eidshaug and his colleagues also applied this same proof of concept to a dictionary of Norwegian as it was spoken among coastal fisher-farmers and other people in the area in the 1840s. And there are many more old dictionaries of languages waiting to be excavated from archive shelves.

In the case of the Yaghan, the hope is that such investigations not only answer archaeological curiosities but also help the living communities engage more deeply with their past. “We’ve connected several times with archaeologists who study artifacts and middens, and it has always been an interesting topic for us Yaghans,” says Zárraga, who spoke with me through an interpreter from her native Spanish language.

Zárraga spent a decade living with her grandmother, learning Yaghan practices, values, and language—and about her grandmother’s experience as the culture around her eroded. “It was ... very pure cultural knowledge that my grandmother had, through the language,” Zárraga recalls. She is working to carry this ancestral knowledge forward in time. She’s already written two educational books on the Yaghan language and has plans for a Yaghan-Spanish dictionary. Eidshaug, meanwhile, has digitized Bridges’ dictionary to make it more easily accessible.

Though media reports often described her grandmother as the last Yaghan speaker, Zárraga hopes her efforts will ensure that the language and its embedded information will not molder in archives, and that the unique culture it described won’t go the same way. “That’s why it’s very, very important, all of these things that my grandma gave me,” she says. “So we are not the last ones.” 🌀

KATARINA ZIMMER is a science and environment journalist currently based in Germany.



The Anatomical Quirk That Saved Dr. No

*A wild tale of how scientists unraveled embryology's
most fascinating mystery*

BY JOHN WALLINGFORD





JULIUS NO CAME UP TOUGH. Abandoned by his parents, he fell in with criminals—and eventually it caught up with him. One night, an assassin aimed carefully at his chest, just left of center, and shot him through the heart. Or so he thought. But Julius didn't die. He went on to medical school, and became an early nemesis of a certain spy named James Bond. Dr. No is a fascinating character, but what surely escapes most fans of Ian Fleming's novels is that the villain's miraculous survival reveals a facet of human anatomy that usually remains hidden—a radical asymmetry of left and right.

The difference between our front and back is so obvious that we rarely think about it; we simply don't have eyes in the back of our head. Top and bottom are obvious, too. Inside, though, asymmetry is everywhere. Heart and stomach lie to the left, the liver to the right. Even our lungs aren't truly paired; the right lung has three lobes, the left two. And anyone who's had appendicitis can tell you about the chirality of our guts. The searing abdominal pain radiates from the lower right, not the left.

Dr. No survived because his assassin quite reasonably assumed the heart would lie to the left, but his victim was among the very tiny fraction of people who are born with their organs reversed, a mirror image called *situs inversus*. And while Dr. No is fictional, *situs inversus* did save the life of at least one real-world gunshot victim, described in a 2020 case study titled, "Shot in the Chest, Saved by the Heart."

How our organs take on these asymmetrical positions is among the most fascinating questions in developmental biology, the science of embryos. The single cell of the fertilized egg divides again and again, becoming trillions, and those cells literally sculpt our bodies. The process by which this happens is almost implausibly baroque. I am a molecular biologist, and in my 30 years of studying embryos, I've found few things quite so fantastical as the tortuous route embryos take to separate right from left.

It's fitting, then, that the story of how we came to understand these mysteries is equally tortuous. It's not simply a story of developmental biology, but one of chronic coughing, sperm that can't swim, a young cardiology fellow, and Japanese street food. Oddly enough, the story opens with another spy, and another doctor named Julius.

UNLIKE MR. BOND, Privy Councillor Karl Ferdinand Zivert hadn't a trace of cloak and dagger panache. It was the decidedly glamourless craft of reading other people's mail that made him a favorite spy of the last emperor of Russia, Tsar Nicholas II. It also made Zivert rich enough to send a son to medical school, and in 1902, that son published a case report in *Russkiy Vrach* (*The Russian Physician*). In it, Alfons-Ferdinand Julius Zivert described just a single patient, a 21-year-old man who'd been coughing violently for his entire life.

The scene in the clinic will sound familiar. The doctor got out his stethoscope, placed it here and there, listened. Then he laid his hands on the patient's chest and abdomen, pressing here and there, pausing thoughtfully. The routine seems perfunctory, but its remarkable diagnostic power has kept it a staple of medicine for 200 years. It also offers the rare opportunity to appreciate your own left and right.

Zivert hoped the sounds in his stethoscope would give up some hint to the nature of that persistent cough. But he didn't hear what he expected; the lung sounds weren't even in the right place. Nor were the heart sounds. Pressing gently, he felt for the liver; it too wasn't where it should be. He listened again, finding the bowel sounds out of place as well. Right there in Kiev, decades before the advent of X-rays, it was entirely obvious

that this patient had been born not just with a cough, but also with situs inversus.

Zivert wasn't the first to observe the condition, so while situs inversus was interesting, it was the cough that fascinated him. Severe and constant, the patient had suffered violent spasms every day since his birth. Whatever was wrong with his lungs, Zivert was certain it had occurred during embryonic development, right alongside the reversal of his organs. In arguing that both the patient's compromised lung function and left-right asymmetry arose during embryonic development, Zivert took a big step. To make sense of what happened next, though, we need first to consider something that happened long before.

IN THE LATE 17TH CENTURY, Antonie van Leeuwenhoek's innovations in microscopy made him the first to see what we now know is an entire world of microscopic organisms.

He had discovered impossibly small creatures in pond water and seawater, but the Dutch fabric merchant was aware of his outsider, even amateur, status. So, he hesitated before exploring another fluid. Did anyone really want him to look that closely at his own semen? Well, yes, actually, he decided, they did. And why stop there? He examined the semen of rabbits and dogs. He discovered there a new creature, one with a rounded head and a long tail that beat rhythmically. It swam!

Fearing the findings were obscene, he described them in Latin to lend a veneer of respectability. In 1677, he sent them to the president of the Royal Society of London, advising him "to publish or destroy them, as your Lordship sees fit." His Lordship did publish them, and that is how the world learned about sperm.

But sperm weren't the only tails van Leeuwenhoek saw wagging in his new



It's a story of sperm that can't swim, a young cardiology fellow, and Japanese street food.

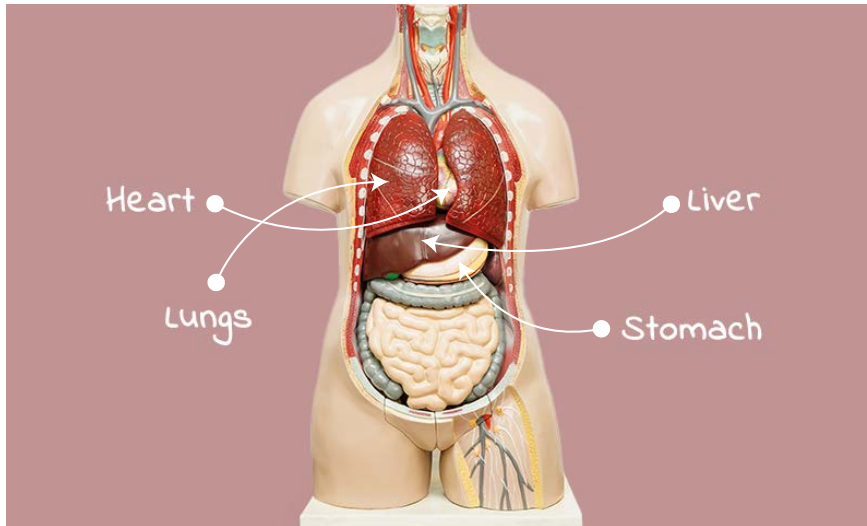
microscopes. Other creatures too were “furnisht with similar instruments in order to make a stir in the water”—tiny aquatic animals studded with hair-like tails called cilia. In the early 19th century, we learned that those creatures with wagging tails includes us. The inside of our lungs and trachea are lined by millions of these cilia. And while they pulse just like sperm tails, the outcome is the opposite. Sperm tails propel the cell through a fluid, but airway cells stay put; cilia propel the fluid. What fluid, you ask? Mucus.

You've probably thought about mucus, at least when you're sick, but while I think about cilia pretty much every day (it's my job), you might never think of them at all. And yet, mucus and cilia form an inseparable partnership. Mucus is constantly produced in a thin layer, and the cilia beat without pause to move it to your pharynx, where you swallow it. All day and night, you are swallowing mucus, and this slimy treadmill is essential to the health of your lungs. It captures and removes inhaled particles, bacteria, and viruses. When your cilia don't beat, mucus can't move; it gets stuck in your lungs, and you cough. Worse yet, you can't clear those pathogens, so you pretty much always have a cold, or even worse, pneumonia. Just like Zivert's patient in Kiev.

Young Zivert knew about the cilia in our lungs, but he hadn't an inkling of how they relate to situs inversus. For decades, neither did anyone else, even as X-rays revealed a whole series of similar patients and forged an irrefutable link between situs inversus and lung disease. Then one day in Stockholm, medical scientist Björn Afzelius was asked to help figure out why some men's sperm don't swim.

AFZELIUS WAS A PIONEER of the electron microscope, and like van Leeuwenhoek before him, he drew back the veil on a whole new world of sperm, seeing *inside* them for the first time. In 1959, Afzelius discovered repeated units inside their waving tails that he called “arms.” Within a few years, the same arms were found in all kinds of cilia, from van Leeuwenhoek's tiny aquatic animals to those in our own airway, a remarkable testament to evolution at work. Today, we know these arms are composed of a molecular motor protein called dynein. Arrayed along the entire length of cilia, they drive the wagging of these extraordinary tails.

It was only natural that Afzelius was asked to examine the sperm of infertile men, for in many patients, sperm are present and look normal, but their tails



TAKING SIDES Heart and stomach lie to the left, the liver to the right. Even our lungs aren't truly paired; the right lung has three lobes, the left two. And anyone who's had appendicitis can tell you about the chirality of our guts.

don't beat. Maybe some defect could be discerned in the electron microscope? Sure enough, his patients' sperm lacked dynein arms.

It was a satisfying discovery, but it wouldn't have made him famous but for the fact that three of the infertile men just kept coughing. Afzelius examined biopsies of their airway cilia, and these too lacked dynein arms. Inevitably, their coughing led to chest X-rays, and those in turn revealed that all three also had situs inversus. Afzelius knew this reversal was rare; it couldn't be a coincidence. The waving of cilia must somehow be connected to the left-right asymmetry of the body.

Embryos develop progressively, starting simply and becoming more complex bit by bit, so the next big question was where and when in the embryo these still-hypothetical cilia did their thing. Afzelius found a clue in the library when he learned that just across the Baltic Sea

in Rostock, Germany—but decades earlier—Kurt Pressler had been tinkering with toads. A practitioner of what is now called “cut and paste” embryology, he used watchmaker's forceps and fine glass needles to dissect out bits of embryos and reimplant them to see how development might be affected. Afzelius was keen on a report from 1911, in which Pressler described the result of a surgery performed surprisingly early in embryogenesis, not just before organs become asymmetric, but before organs even become.

Embryos lay out their principal axes in a process called gastrulation, at the end of which an expert can discern front from back, head from tail. But at this early point, the embryo still has no organs; left and right exist only as geometry. Nonetheless, Pressler found that when a small part of the back was removed at this stage, rotated 180 degrees, and re-implanted, then some weeks later the organs developed with complete situs inversus.

Pressler said nothing of cilia, but Afzelius sensed the flow of evidence perfectly. Today, we know that motile cilia on that rotated bit of an early frog embryo *do* control left and right. Cilia in the equivalent region of early mammalian embryos, including humans, do the same. But Afzelius couldn't prove it, and he complained that he couldn't test his idea with "a more specific interference."

Ironically, the very "interference" that ultimately proved Afzelius right had already been discovered, 15 years before his lament. He just didn't know about it. This was long before the internet, and anyway, it hadn't come from his colleagues studying male fertility, or from electron microscopists, or even from developmental biologists. No, that discovery came from an expert in breast cancer, a mouse geneticist in Bar Harbor, Maine.

KATHERINE HUMMEL WAS NEVER particularly interested in situs inversus. When the double helix structure of DNA was discovered in the 1950s, she was well known for her studies of the genetic basis of cancer. Cancer runs in the family, not just in humans but in mice as well. Hummel had found such mouse families, and by reliably developing tumors, they allowed her to test treatments, and to glean insights. And, in breeding generation upon generation of mice, she inevitably found new families, with new traits. Families of mice with diabetes, families prone to obesity. One day, she observed a litter of suckling pups, their nearly transparent newborn skin revealing tiny white stomachs filled with milk.

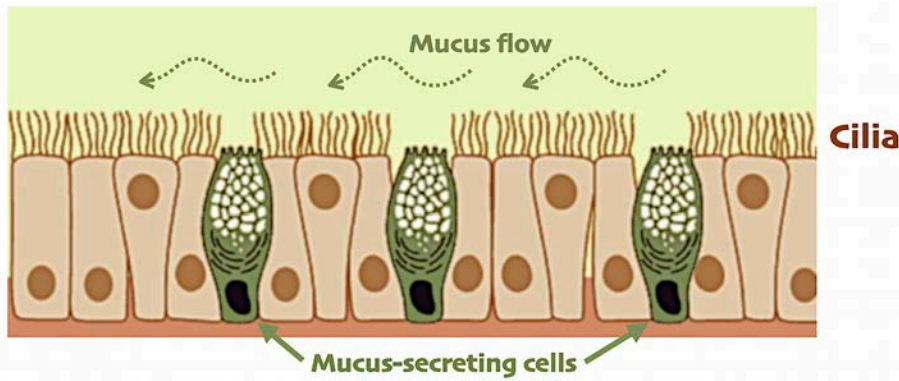
To her surprise, two of the pups had that white spot on the right, not the left. She bred the mice further and found that situs inversus was a genetic trait. It ran in the family. She also found that only

Sperm weren't the only tails van Leeuwenhoek saw wagging in his new microscopes.

a single gene was responsible, but with the revolution of molecular biology still decades away, she had no idea which gene. Just the same, she dutifully published a paper describing the mice in 1959, the very year Afzelius had first found arms in cilia. Hummel never studied the mice again, though others did, and like some rodent royal bloodline, the family bred true for dozens of generations.

In the 1990s, a new breed of "molecular geneticists" started to link such families of mice to specific genes. One of these was Martina Brueckner. Born the same year Hummel published her paper, Brueckner used the descendants of those two pups to add the next piece to Zivert and Afzelius' growing puzzle.

The mouse genome has nearly 3 billion individual units, and Brueckner found the tiniest possible change. In the ATCG language of genes, changing a single G to an A in the DNA was enough to cripple the dynein motor in the arms; cilia in these mice cannot beat. Even more excitingly, she found that the gene is active specifically in a region of the early mouse embryo called the node, the anatomical equivalent of that rotated bit in Pressler's toads.



INSEPARABLE PARTNERSHIP The airway mucociliary system. Mucus-secreting cells (green) constantly produce a thin layer of mucus. Directionally beating cilia that extend from so-called multiciliated cells (brown) propel it to the pharynx, where it is swallowed.

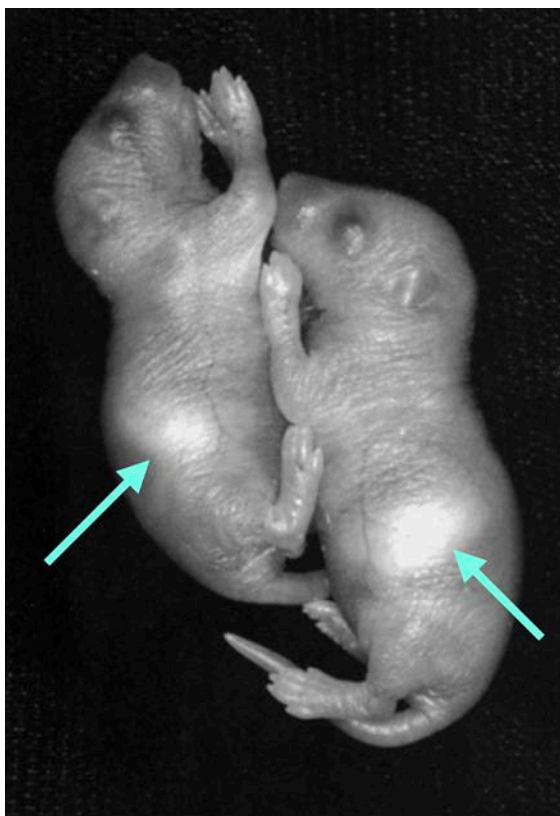
SHIGENORI NONAKA READ Brueckner's paper closely. Half a world away in Japan, he was using video microscopy to make movies of this very region of the mouse embryo, the node. He saw cilia beating there, but more importantly, he was able to add tiny beads to the fluid around the embryo and track their motion. Like mucus marching toward the pharynx, the beads revealed a striking, robust flow across the node. And it was always from right to left. When he did the same with the mice with situs inversus, the beads didn't move at all. But while it's obvious enough how infertility results if sperm can't swim, or that mucus accumulates if airway cilia don't beat, it wasn't at all obvious why or how flow of fluid across the node could cause left-right asymmetry. So, seeing the flow just wasn't enough; Nonaka remembers his mentor insisting he find a way to change it.

Nonaka set aside the modern tools of molecular genetics and took up the century-old tools of cut-and-paste embryology. Using forceps and fine needles that

Pressler would recognize, he carefully dissected early mouse embryos out of the uterus and away from the placenta. Just handling these tiny embryos, perhaps half a millimeter long, is hard enough. But getting them to stay still? And creating an equally tiny flow of fluid across them? It seemed impossible.

Inspiration arrived from two unlikely sources: Japanese street food and the oil industry. *Takoyaki* is a fried octopus treat popular near Osaka. To position his embryos, Nonaka "trapped" them using tiny closed-end chambers he crafted to resemble traditional octopus traps. The embryos were held in place with the ciliated node waving in the fluid outside. Then, after seeing a picture of devices that smooth the flow of oil through refineries, he fashioned a similar but miniscule pump to generate a smooth but tiny "stir in the water," to borrow van Leeuwenhoek's phrase from centuries before.

The contraption worked. Nonaka could precisely control fluid flow across the mouse node. When he drove it



MILKSPOTS Martina Brueckner's picture of two of Hummel's mice. The white, milk-filled stomach (arrow) is normally positioned on the left side, as in the mouse on the left. Its littermate on the right has situs inversus, its milkspot obvious on the right side of its body.

Even flipped, if they are connected in the right way, their physiology is normal.

But there is a dark side to our left and right. Imagine a *partial* reversal, for example where the heart is flipped but the lungs and liver are not. How could the veins and arteries connecting them find their way in the embryo to the right part of each organ? The

leftward, all of the embryos developed normally. When he reversed the flow, they developed situs inversus. Leftward flow, controlled by normal cilia with healthy arms, he reasoned, causes cells on the left side to turn on developmental genes that remain silent on the right.

FOR DR. NO, situs inversus was a blessing, but for most people it simply is: It makes little impact on a person's health. One woman even became a minor celebrity, posthumously at least, when an autopsy found she'd lived 99 years without ever knowing her organs were reversed. It's easy to imagine how. A British car with the steering wheel on the right seems strange to Americans, but it drives just fine. So, too, with our organs.

fact is, they often don't. Situs inversus has long been linked to a risk for birth defects, especially those affecting the heart. Hummel noted them in her mice; Pressler's toads had them, too.

Martina Brueckner knows this dark side all too well. She discovered that 1-in-3-billion genetic anomaly, but she didn't set out to be a geneticist. She's a pediatric cardiologist, and the kids in her ICU at Yale Medical School are often very, very sick.

When she was still a fellow, mice with situs inversus seemed a reasonable topic for a short, mandatory research project. But when she first set foot in a mouse colony, she saw those tiny milk-filled stomachs on the wrong side and was hooked. She didn't stop with finding the gene

MARTINA BRUECKNER

One woman became a minor celebrity when an autopsy found she'd lived 99 years without ever knowing her organs were reversed.

in Hummel's mice; she's spent the past 25 years looking for and finding genes related to our own left and right. Sadly, these discoveries usually come from kids with heart defects.

And this work is important, because partial reversal of the organs (called heterotaxy) is frequently lethal. Indeed, birth defects are the number one cause of death for babies in the United States, and more than twice as lethal as pediatric cancer for children of all ages. Heart defects are the most common among them, and while some are treatable with surgery, others are incurable.

Now, a host of studies launched by Brueckner, Nonaka, and others working with animal models is enabling us to find genetic variants—subtle ATCG changes like the one in Hummel's mice—that cause heterotaxy in humans. With advances in human genomics and preimplantation genetic diagnosis, we're starting to see a path forward to preventing not just congenital heart defects, but perhaps even the lifelong cough that Zivert's patient suffered.

BACK IN DR. NO'S UNDERWATER LAIR, James Bond pours a third martini from the shaker. His host with the inverted anatomy parts his thin lips and recounts the aftermath of his brush with death. "I hid myself in the academic world," he explains, "the world of libraries and laboratories. And there, Mr. Bond, I lost

myself in the study of the human body and human mind. Why? Because I wished to know what this clay is capable of. I had to learn what my tools were before I put them to use."

Absent the villainy, Zivert's goals were the same. So, I wonder about him, and how he returned home that April day after seeing his coughing patient. He must have been puzzled. But could he imagine the convoluted epic of real-life libraries and laboratories that would follow? How slowly we'd learn what the clay is capable of?

Over dinner, James Bond considered his nemesis: "The incredible biography rang true. Not a word of it impossible." Biology follows a similar script, one that's incredible but true: What looks like no more than the slightest wiggle in an embryo commands the whole of an invisible axis inside the body and governs the function of the sperm, the lungs, and the heart. ☺

JOHN WALLINGFORD is the Mr. and Mrs. Robert P. Doherty, Jr. Regents Chair in Molecular Biology at the University of Texas at Austin. He is a 2022 Guggenheim Fellow and a past president of the Society for Developmental Biology.



Ranchers, Cattle, Tequila, and Bats

A tale of ecological salvation in Mexico

BY HILLARY ROSNER

IN A MEXICAN SCRUBLAND DESERT, a small bat flies by night, journeying hundreds of miles, pausing briefly to feast on the pollen of a singular flower: the wild agave plant. Agave plants bloom only once in their lifetime—taking 10 or even 20 years to do so. And the Mexican long-nosed bat (*Leptonycteris nivalis*) depends on these rare blooms exclusively for food as it travels from breeding grounds to birthing grounds and back again. In return, the bat pollinates the plants, laying a pathway forward for the next generation of this nectar highway.

The bat and its increasingly scarce agave flowers have danced in a delicate and intimate partnership for millennia. But they have been falling out of step as populations of both have taken a nosedive over recent decades. The partnership, however, is vital not just to their own survival, but also to the larger ecology of the region and to the people who make their lives on this land.

Small ranching communities, known as *ejidos*, dot the remote, dusty landscape. Years of drought and desertification have made an often tough existence there even tougher; some of the *ejidos* have been abandoned in recent years. But the bats and agave might bring salvation. With help from big-thinking bat conservationists, the solution could also benefit the soil, local ranchers and farmers, and the ecosystem as a whole.

THE MEXICAN LONG-NOSED BAT lives mainly in desert-scrub woodlands and migrates along a 700-mile stretch from central Mexico up to southwestern Texas and the very bottom edge of New Mexico. It has ash-colored fur, a 14-inch wingspan, a leaf-like nose flap protruding skyward from its snout, and a narrow tongue that can extend out 3 inches—about as long as its entire body—to extract nectar from the agave plants, its sole food source during parts of the year.

Mexican long-nosed bats mate in the spring, and the pregnant females head north, surfing a wave of agave blooms up through northeastern Mexico. Along the way, they stay in caves or abandoned mines for days or weeks, until finally reaching their maternity roosts on either side of the border. There, these

endurance-athlete moms give birth to one baby each, and those little bats must stay in their caves for six weeks before they can fly. In late summer, the moms and their young make the journey in reverse, feeding on species of late-blooming agave.

There are more than 200 species of agaves, including dozens native to northern Mexico. These spiky succulents grow a giant stalk that towers as high as 20 feet, depending on the species, and then erupts in a feast of nectar-laden flowers. Afterward, they die. Their dried-up stalks remain for a time, like ghost trees rising from the scrub.

Agaves are keystone plants, crucial not just for bats but for a whole host of species. Hummingbirds also drink their nectar and pollinate them. Woodpeckers roost in the stalks and will also drink the nectar. Rattlesnakes make their home in the bases. “Crows, ravens, ringtail cats, foxes, deer,” said Kristen Lear, an American bat biologist and agave restoration program manager for Bat Conservation International (BCI), rattling off a list of species that use agaves. “Tons of animals. Agaves are just super important.” And like other native plants, they hold water that keeps the ecosystem more lush; they also help reduce soil erosion and store more carbon dioxide than most other plants.

Agaves were once plentiful across the bats’ entire migration route. But now, the bats are finding fewer and fewer of the flowering succulents to fuel their journey. There are a number of reasons for the agaves’ decline. Urbanization and development, along with agriculture and livestock grazing, have destroyed large swaths of habitat, leaving less and less undisturbed



IN THE DARK The Mexican long-nosed bat feeds on nectar from wild agave plants as it migrates hundreds of miles through the desert. These agaves, however, flower only once in their lifetime, and are becoming more and more rare, creating a cascade of ecological impacts.

desert scrubland. A prolonged drought has made agave survival and regeneration more difficult in the areas that remain. Global warming has left this region, like so many others around the world, hotter and drier. When excessive heat and low rainfall reduce the amount of grasses available for cows and goats to eat, the hungry animals turn to other plants, including agaves. They will eat the leaves and the stalks, which are sugary and rich in energy. Ranchers sometimes cut the stalks down at

the base just as they are flowering and leave them in the field for their herds. This deals a double blow: no nectar for bats and no pollinated seeds to grow into new agaves.

All of this causes a larger ecological feedback loop. The destruction of landscapes once filled with native plants leads to further desertification; when people clear the land for farming, or allow livestock to overgraze it, the entire system gets drier. The many gold,

NILUPA DILSHAN / SHUTTERSTOCK

Agave plants bloom only once in their lifetime—taking 10 or even 20 years to do so.

silver, and copper mines scattered throughout the area further dehydrate the system by sucking up groundwater, making it more difficult for agaves and other plants to grow. In parallel, Mexican long-nosed bat numbers have continued to decline, leaving fewer pollinators to keep the remaining agave populations going.

Bats in general are struggling, all over the world. About a quarter of all bat species are either endangered or threatened, and in the United States more than half of all bat species are “at risk of severe population decline in the next 15 years,” according to BCI. “That’s a lot of species that are under threat,” says Lear. A combination of habitat loss, climate change, and the deadly “white nose syndrome” fungal infection have thrown many populations into a downward spiral.

The Mexican long-nosed bats, as well as their cousins the lesser long-nosed bats, which also migrate through the region, evolved with a pathway of blooming agaves. (Lesser long-nosed bats, whose populations have recovered in recent years, also feed mainly on agave nectar for most of their journey—along a more westerly path—but at the northern end of their route they eat nectar from large flowering cacti, such as saguaro. This varied diet has likely helped their recovery.)

Just like guests at roadside hotels on asphalt highways, nectar-feeding bats also need warm, safe places to sleep. In the 1990s, there were roughly 30 known roosting caves for Mexican long-nosed bats, each containing thousands of individuals. But over the past 25 years, many of the original caves that once sheltered

the bats have become inaccessible or inhospitable to them. “They’re empty of bats,” said Ana Ibarra, a Mexican bat biologist and strategic advisor for endangered species for BCI. “They have been built over, they have been closed off, they have been used as dumpsters.” Today just 10 of the roosting sites remain, and scientists fear there are only between 6,000 and 10,000 of the bats left.

AGAVE, TO MANY PEOPLE, means not bats but alcohol: tequila and mezcal, agave-based spirits whose sales have increased nearly three-fold over the past two decades in the U.S. But while it might seem that growing agaves for these products would help the bats, the opposite has proved true. Producers often clear native plants to put in a monoculture crop that fails to provide the diversity necessary to sustain thriving communities of wildlife. Then, they typically harvest the agaves before the plants have a chance to flower—which leaves nothing for nectar-feeding bats to eat.

Some smaller producers, mainly of mezcal, allow a portion of the plants to flower. But most don’t. A Bat Friendly tequila and mezcal label had aimed to certify farms that let at least 5 percent of their crop flower, but only two brands were using the label as of 2021, the last year listed on the group’s website. Consumers, Ibarra pointed out, could demand change. “People that think they are totally removed from the game,” she said. “They’re not removed from this. There’s responsible consumption.”

The pregnant bats head north, surfing a wave of agave blooms up through northeastern Mexico.

In the meantime, to help save the nectar-feeding bats, BCI is working to replant and conserve agaves all along the bat migration corridors, and to safeguard the animals' roosting sites. This means partnering with the *ejidatarios*, the farming and ranching families living in the *ejidos*, to restore degraded lands, harvest seeds, grow new agaves, and monitor bats. "The idea is that if we can restore the soil, water, native grass, that will create healthy habitat for these agaves to flourish," said Lear. All of that helps the *ejidos*, too. "By restoring the habitat for the bats, we also restore the land for the people," Lear said. Humans and nature can't exist in isolation from each other; nature and culture are inextricably connected.

THE MEXICAN LONG-NOSED BATS had made their late-summer journey south by the time I flew south to Mexico and headed for Matehuala, the small city in San Luis Potosí that's the closest town to many of the *ejidos* working to protect the bats. The mother and baby bats had by this time reunited with the males in caves near

Mexico City, about 400 miles south, where they would spend the winter. Ibarra, Lear, and I spent the night in Matehuala, and in the morning, we picked up provisions at the local Walmart and set out for the desert with a team from Comisión Nacional de Áreas Naturales Protegidas, the federal government agency that oversees Mexico's protected areas. In the remote mountains near the border between San Luis Potosí and the neighboring state of Zacatecas lies a small conservation area called Mojonera, which is made up of land owned by seven *ejidos*. Mojonera and the *ejidos* together occupy a landscape of agave habitat that is vital to the survival of nectar-feeding bats.

Despite sharing the same general landscape, there were distinct differences from one *ejido* to the next. Variations in rainfall patterns as well as in historic land use made for noticeable shifts in the quality of the soil, the feel of the air, and the health of the agaves that the *ejidatarios* were planting, backed by funding from BCI. At Coyotillos, an *ejido* located in Zacatecas state, José Inocencio Moreno Mendoza took us to the field where



he had planted rows and rows of agaves he and his wife had germinated from seed in the nursery. They were experimenting with a non-native agave species that was fast-growing and might flower in fewer than 10 years. There were also rows of prickly pear cacti, or nopal, which are harvested as a crop, and some native plants like mesquite and a kind of small, green pumpkin that's used to make soap. But the field was dry and dusty, and many of the agaves looked like they were barely hanging on, leaves brown and shriveled. Still, Lear was confident they would survive. They were adapted to the desert, after all.

"This used to be a farm field, but when the rain stopped coming, nothing could grow," said Lisette Leyequien, who oversees Mojonera, as she walked the rows. She hoped the agave might help keep the field from turning to desert—which would also help Mendoza and his family continue to grow crops and make a living on the land. "If the agave can't even grow, corn can't grow. Then the soil erodes," she said. The soil was so compacted in places that it could no longer hold water even when the rains did come. It simply washed away.

The sun was blazing down. The air, like the soil, felt desiccated. We crossed a line of shrubby mesquite to another field, where the soil was darker and not as dry. Here, many of the agaves looked healthy and thriving—they were half a foot taller than the other ones, with strong green leaves poking skyward. Some infinitesimal difference from one field to the next—in rainfall, slope, perhaps past practices—seemed to have made a difference.

In each *ejido* that was helping restore the agave corridor, BCI was also working with the communities to diversify their farming practices and even their livelihoods to create a more sustainable landscape economically as well as ecologically. Down a dusty road, residents of Cuatro Milpas ("four cornfields") had germinated hundreds of agaves, and these were thriving in a nursery. There, money from the agave effort had gone toward a small portable mill that enabled the ranchers to grind up invasive Russian thistle—tumbleweed—into cattle feed, providing an additional source of food that could help take some of the pressure off of the native agave plants. The ranchers also used the mill to grind up agave leaves into a watery pulp, which

they mixed with molasses and fed to the cattle as well. Now the agave was benefitting the *ejidatarios* as well as the bats.

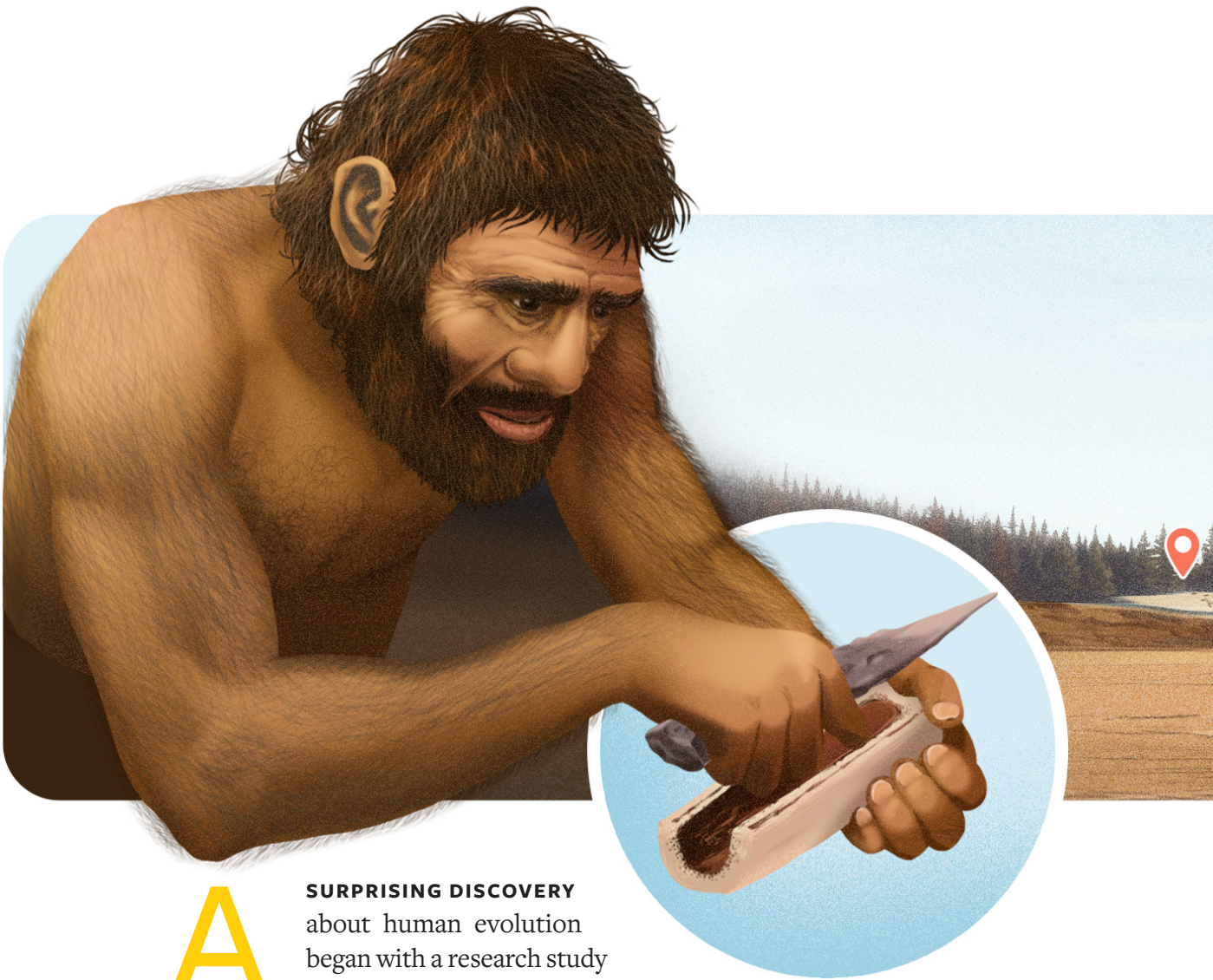
Harvesting the outer leaves of the agave does not harm the plant; in fact, it can stimulate the plant to produce "pups," clonal babies that emerge from tendrils and will grow into new agaves. This is one of two ways that agaves reproduce, but because it creates a genetically identical plant, it doesn't preserve the genetic diversity necessary for the species' survival. For that, it needs to reproduce via pollinated seeds, which is where the bats and other pollinators are essential.

Watching the *ejidatarios* grind weeds into cattle fodder under the bright desert sun, it was easy to forget all about the bats. We were hundreds of miles from the small winged mammals, which would at that moment have been sleeping the day away in a warm cave near the capital. But the bat biologists grinned as tumbleweed dust filled the air. Their project was materializing before their eyes. "As biologists, we learn about so many things," Ibarra said. "I'm learning about livestock food!"

Lear nodded. "Who knew bat biologists would be learning to feed cattle?" They were rebuilding a chain of survival for the migratory bats, using spiky desert succulents and bonds between people. "Bats are migrating such long distances, across boundaries, bringing people together," Lear said. "I always think about the social connectivity. They connect actors across that corridor." But because agaves take so many years to flower, the work Lear oversees is not just about bat-plant and bat-people connections. It's also about "connecting timescales," as she put it—planning for agaves, bats, and people to coexist into the future. ☺

HILLARY ROSNER is an award-winning science journalist and assistant director of the Center for Environmental Journalism at the University of Colorado Boulder. Her stories about the natural world have appeared in *The New York Times*, *National Geographic*, *The Atlantic*, and dozens of other publications.

Adapted from *Roam: The Race to Knit the Natural World Back Together*, to be published by Patagonia Books in 2025.



A

SURPRISING DISCOVERY

about human evolution began with a research study about, surprisingly, birds.

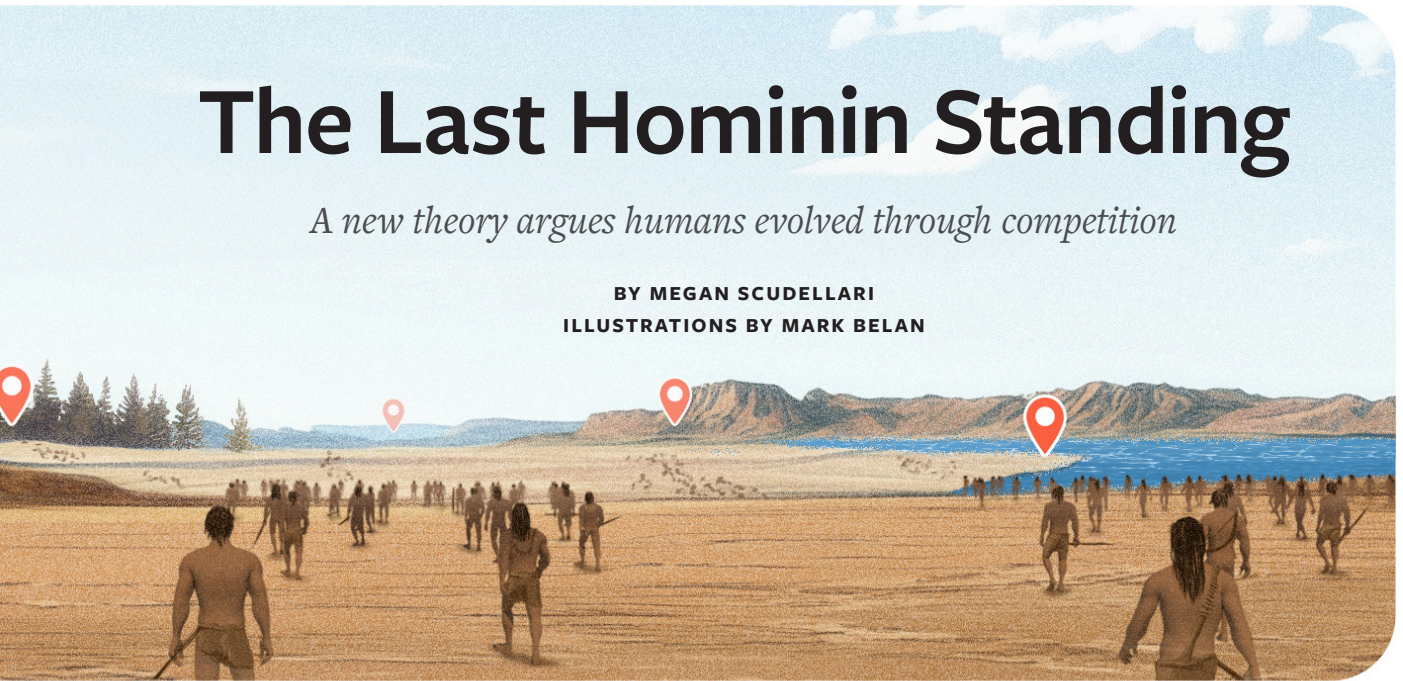
Five years ago, evolutionary biologist Laura van Holstein at the University of Cambridge read a study on the role of competition in songbird evolution. The work, from an international team of evolutionary biologists, found that competition between interacting species of songbirds—over food, mates, and territory—drove the evolution of new traits, such as beak shape, across long timescales and large distances in Central and South America. For years after reading the study, a question lingered in van Holstein's mind: Did competition also drive the evolution of hominins, the evolutionary branch that includes humans and our ancestors?

The Last Hominin Standing

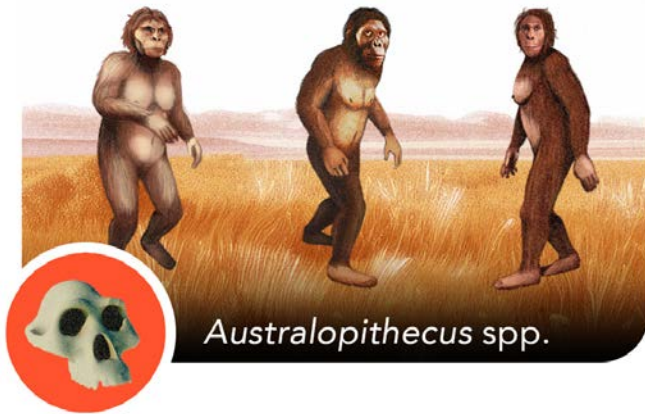
A new theory argues humans evolved through competition

BY MEGAN SCUDELLARI

ILLUSTRATIONS BY MARK BELAN



Competition is a major part of natural selection and central to the theory of evolution, yet no one had formally investigated competition between hominin species before, for two likely reasons. First, most human evolution studies focus on climate as the main driver of hominin evolution. Key events in hominin evolution—such as the first use of stone tools and increases in brain size—coincided with major changes in climate, such as the rise of the dry savanna in Africa. So, scientists have spent a lot of time studying how fluctuations in Earth’s climate may have led to adaptations that shaped our species. Second, there simply hadn’t been enough hominin fossils overlapping in time and place to think that competition among those species was a big deal.



Australopithecus spp.



Paranthropus spp.



Homo spp.

However, over the past 15 years, many more hominin fossils and species have been discovered, so van Holstein finally had the chance to investigate her lingering question. Using computer software and mathematical models, she and evolutionary anthropologist Robert Foley analyzed a wealth of fossil data to explore competition in hominin evolution. They focused on three subgroups of hominins: the small-brained, ape-like *Australopithecus*, the huge-headed *Paranthropus*, and our own group, *Homo*.

What they found in our own branch of the evolutionary tree came as a shock—the complete opposite of a pattern found in other vertebrates. For *Australopithecus*, *Paranthropus*, and other vertebrate groups, as the number of species in a group went up, competition increased, and the rate of forming new species slowed down. In *Homo*, as the number of species went up, competition increased, and the rate of forming new species got even faster. The results, published in the journal *Nature Ecology & Evolution*, challenge previously held beliefs about the history of our species, and raise new questions about how competition formed us into the species we are today.

For the study, van Holstein gathered location and carbon dating information for fossils from 17 hominin species, then used that data to model when a species originated, how long it existed for, and when it disappeared. Next, she ran a mathematical model to calculate and compare how competition—that is, having more than one species in the same location at the same time competing for the same resources—affected speciation and extinction of the three hominin subgroups.

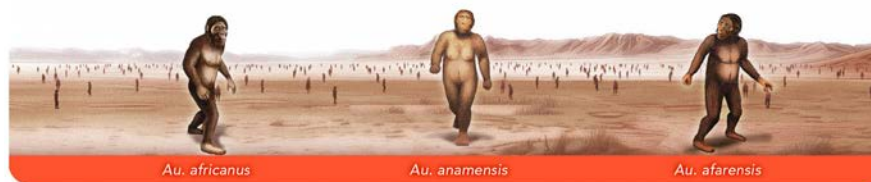
The first results emerged for *Australopithecus*, a genus made famous by “Lucy,” a petite, well-preserved fossilized skeleton from Ethiopia, and *Paranthropus*, whose broad molars and gorilla-like skull suggest these animals had huge chewing muscles. Based on the researchers’ estimates, competition drove the evolution of these two

subgroups as expected: As the number of species increased, competition over resources such as food, water, and shelter increased, and fewer new species evolved while more species went extinct. In other words, as the number of species increased, the rate of forming new species slowed down.

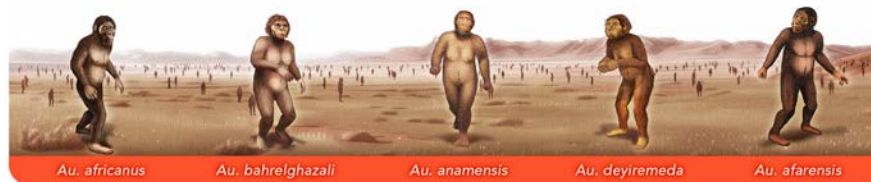
Then van Holstein ran the model for *Homo*. The results were so surprising, she thought, “This can’t be.” So she ran the model again. Same results. She put the data into a different model, and another. Each time, she saw the same, unusual pattern. *Homo* was an outlier.

Speciation and Diversity of *Australopithecus* spp.

Between 4 – 5 million years ago



Between 3 – 4 million years ago



Between 2 – 3 million years ago



Between 1 – 2 million years ago



The timeframes in the illustrations of each species—spp.—are drawn from the scientists’ recent estimates.

What they found in our own branch of the evolutionary tree came as a shock.

Speciation and Diversity of *Paranthropus* spp.

Between 3 – 4 million years ago



Between 2 – 3 million years ago



Between 1 – 2 million years ago



Speciation and Diversity of *Homo* spp.

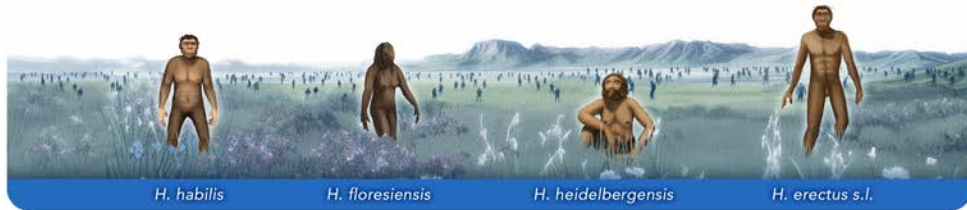
Between 2.5 – 3 million years ago



Between 2 – 2.5 million years ago



Between 1 – 2 million years ago



Between 0 – 1 million years ago



Present Day



Unlike *Australopithecus*, *Paranthropus*, and other previously studied vertebrates, such as birds, the more species of hominins that emerged, the faster new *Homo* species formed and fewer *Homo* species went extinct. And that, van Holstein says, is “really weird.”

As with most unexpected discoveries, the scientists then asked, “Why?” They formed two hypotheses.

First, perhaps as there were more hominin species and competition increased, ecological niches where one could find food and shelter became scarce, and there was pressure to make new niches. Instead of going extinct or no longer producing new species, *Homo* responded with technology, such as the use of primitive tools and fire. In this way, a *Homo* species could have used technology to create a new niche in the local environment—such as being able to access a new food source—and then adapted to that new niche, forming a new species. Competition begets more species.

Another possibility arises from the fossil evidence that *Homo* species spread out geographically, the only hominin genus to expand its range outside of Africa. It may be that increased competition led to increased *Homo* expansions into new habitats, prompting new adaptations and more speciation.



“At a fundamental level, it’s always cool when a new result challenges how we think about our own story,” says van Holstein. Next, she plans to investigate competition between hominins and other species, such as pigs and monkeys, and how competition influenced the evolution of hominin traits such as brain size and body mass.

And there are always more lingering questions, such as what changed when *Homo sapiens*, our own species, finally evolved. “What the hell did *Homo sapiens* do? We exist in every single niche. How does our species fit into this narrative of evolution?” asks van Holstein.

The final narrative has yet to be written, but the story so far is rich with possible outcomes. Of at least 20 known hominin species that evolved over 6 million years, all but one disappeared.

Starting around 40,000 years ago, *Homo sapiens* became the sole survivor. Some evolutionary biologists believe *Homo species* had an edge over other hominins, such as *Paranthropus*, by living in complex family groups, building shelters, and using fire—traits that likely made *Homo* more resilient and adaptable than other hominins. Once *Homo* became dominant, *Homo sapiens* may have outlasted other *Homo* species through increased cognitive powers, such as problem-solving and building more, varied tools. Or, it's possible that other *Homo* species succumbed to natural disasters, disease, or climate shifts. In that case, the mighty *Homo sapiens* was the last species standing, purely by chance. 😊

MEGAN SCUDELLARI is a science writer based in Boston, specializing in the life sciences. Her work has been featured in the *Boston Globe*, *Nature*, *Newsweek*, and others. She is also co-author of a college biology textbook, *Biology Now*.

MARK BELAN is a scientific illustrator and information designer. He operates artsci studios, a scientific graphics and visual communication studio supporting all scientific disciplines. His work has appeared in popular science media such as journals, magazines, exhibitions, and museums worldwide.

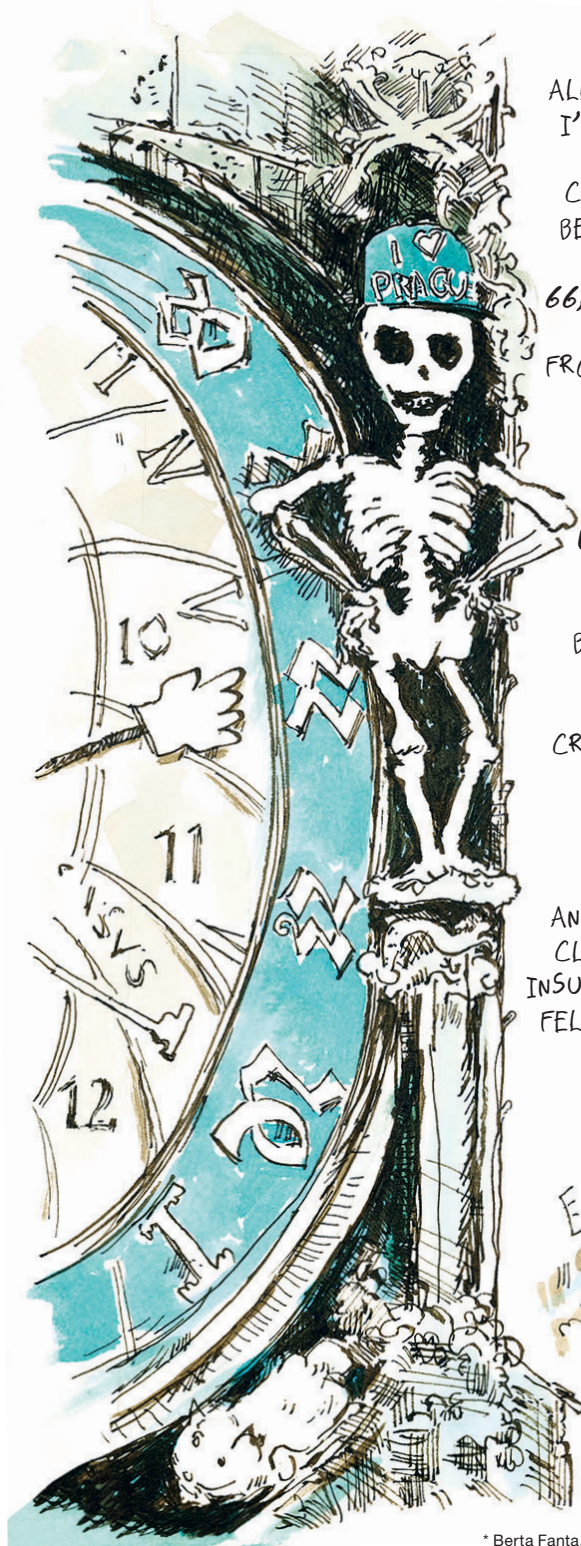


The background is a dark, moody, and abstract composition. On the left side, there is a vertical, metallic-looking object with a textured, possibly crystalline or mineral surface, which appears to be part of a larger structure. The rest of the image is a dark, swirling, and textured expanse of colors, primarily in shades of dark blue, black, and deep green, giving it a cosmic or ethereal feel.

When Einstein and Kafka Met

Imagining a conversation between the two great minds

BY KEN KRIMSTEIN



ALLOW ME TO INTRODUCE MYSELF.
I'M THE SKELETON WHO GRACES
THE FAMED ASTRONOMICAL
CLOCK IN PRAGUE, WHERE I'VE
BEEN RINGING THE HOURS SINCE
1410—A LITTLE MORE THAN
66,352,553 TIMES AT LAST COUNT.

FROM MY PERCH, I'VE SEEN IT ALL.

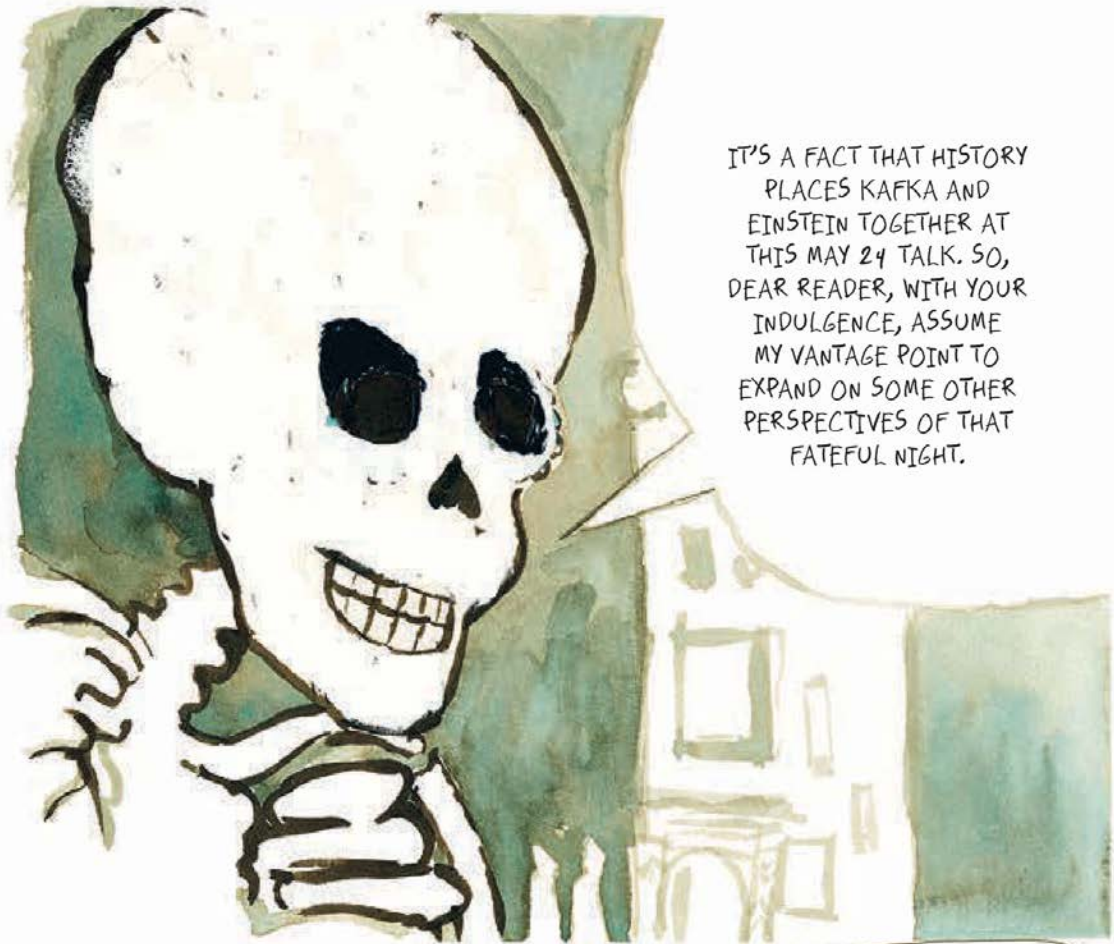
BUT NOTHING COMPARES TO
WHAT I WITNESSED BETWEEN
APRIL OF 1911 AND JULY OF
1912 IN THAT SOUVENIR SHOP
ACROSS THE SQUARE.

BACK THEN, IT WAS THE WHITE
UNICORN PHARMACY, WHERE,
EVERY TUESDAY, THE POET,
CRITIC, AND MYSTIC BERTA FANTA*
HOSTED PRAGUE'S BEST AND
BRIGHTEST FOR DISCUSSION,
MOZART, AND STRONG TEA.

AND WHERE A FRUSTRATED PATENT
CLERK AND AN AMBITIOUS YOUNG
INSURANCE EXECUTIVE UNEXPECTEDLY
FELL INTO EACH OTHER'S COMPANY.



* Berta Fanta, 1865–1918. First woman graduate of Karl University in Prague, at that time called the Charles-Ferdinand University.



* His father Hermann, desperate for his son to get a practical job, arranged several interviews to become an insurance agent and it's said that the frustrated fledgling physicist even tried his hand at selling policies for a few months.



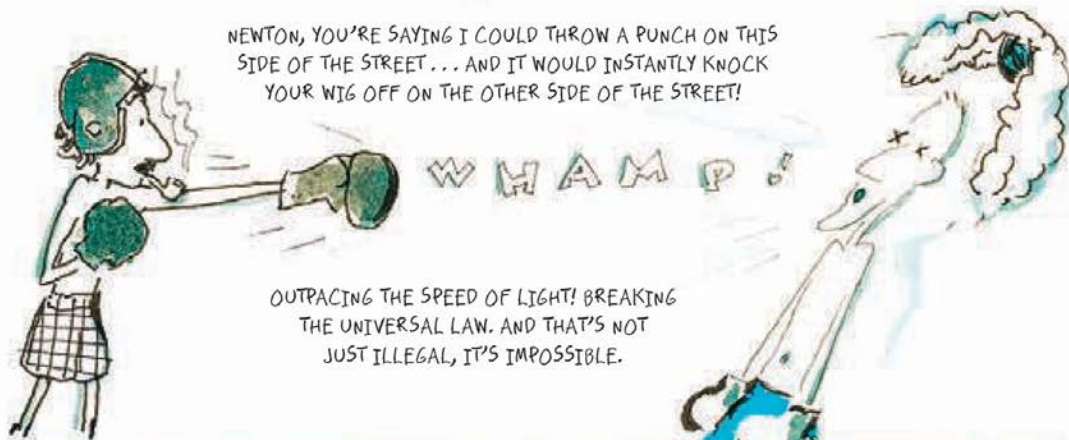


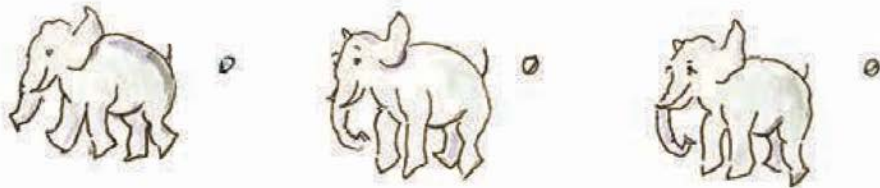
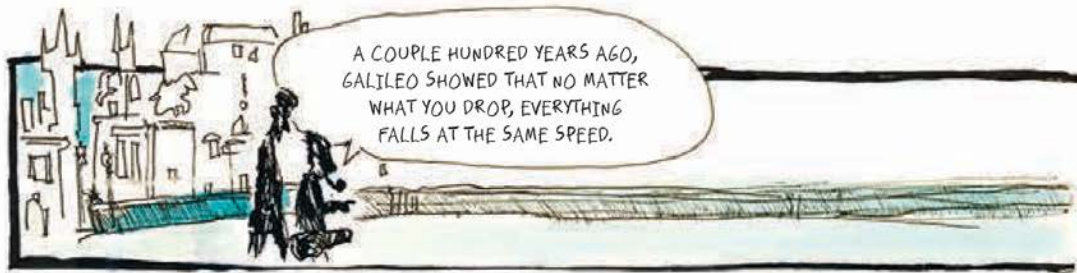
* And write the first ever sci-fi novel!





* The perihelion of Mercury, an anomaly of Mercury's orbit that didn't square with Newton's math, that vexed physicists for more than 200 years, and that was perfectly explained by Einstein's eventual insights.

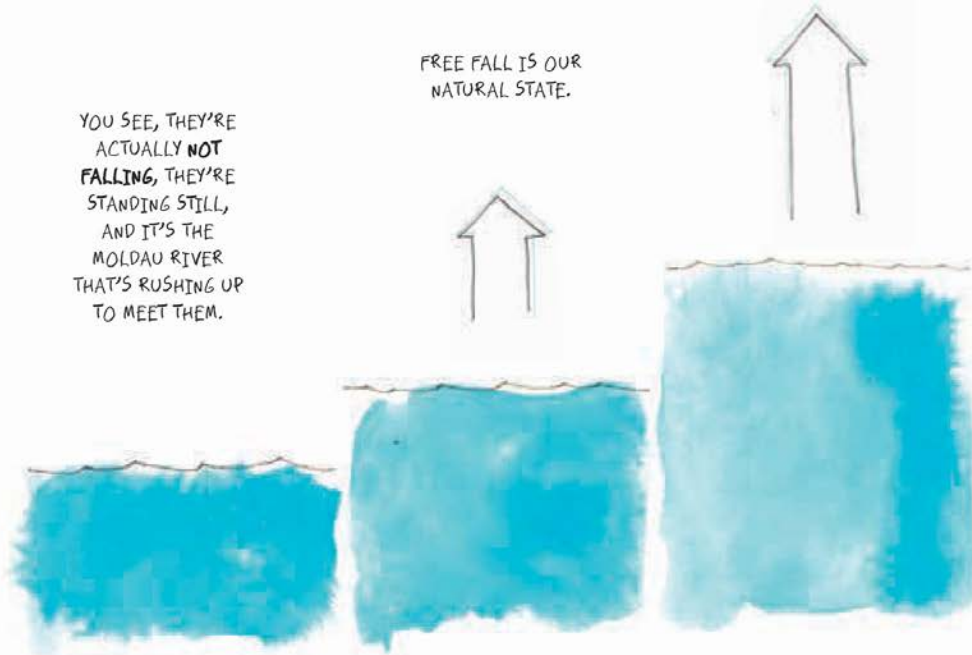


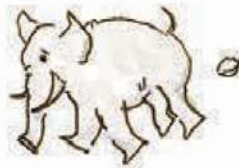
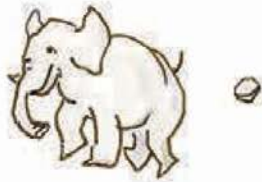


IT'S THE WEIGHT OF THE EARTH AND EVERYTHING ELSE IN CREATION...

FREE FALL IS OUR NATURAL STATE.

YOU SEE, THEY'RE ACTUALLY **NOT FALLING**, THEY'RE STANDING STILL, AND IT'S THE MOLDAU RIVER THAT'S RUSHING UP TO MEET THEM.





AND UP UNTIL ...

... THAT MAKES THE RIVER
RACE UP AND UP AND UP

SPLOOSH





WHAT THE HELL MAKES ME THINK I CAN "SOLVE GRAVITY"?



IT'S CALLED AN OBSESSION, ALBERT. AND IT'S REAL.







KEN KRIMSTEIN has published cartoons in *The New Yorker*, *Punch*, the *Wall Street Journal*, and more. He is the author of *The Three Escapes of Hannah Arendt*—which won the Bernard J. Brommel Award for Biography and Memoir and was a finalist for the Jewish Book Award and the Chautauqua Prize—and also of *Kvetch as Kvetch Can*. He lives and writes and draws in Evanston, Illinois.

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The Lion Who Would Save the World

An anthropologist shows how bonding with another species could help humans come together

BY HARVEY WHITEHOUSE



RUNNING ALONG THE OUTER PERIMETER of Hwange National Park in Zimbabwe is a railway line. From a lion's perspective, the railway line is just a strange feature of the landscape—two lines of shiny metal whose occasional vibrations lead to a thunderous stampede of cube-shaped animals on spinning metal feet that appear and vanish, leaving behind only a faint scent of fossil fuels and human bodies. But when there are no trains around, there is nothing to fear from the steely tracks.

Living in the New Guinea rainforest showed me how groups bond through emotionally intense rituals.

Cecil the lion often wandered up to the railway line and then turned back to the national park. But on other occasions, he felt his prospects of finding food and adventure might be better on the other side of the tracks. July 1, 2015, was one of those days.

There was something here, though, that Cecil couldn't fathom. He could be legally shot by people from rich countries far away. At around 10 p.m., an American trophy hunter, Walter Palmer, wounded Cecil with an arrow. During the night that followed, Cecil no doubt suffered great pain. After the sun rose the next day, Palmer and his professional hunting guide tracked down Cecil and Palmer delivered a final arrow. Cecil met his death at around 9 a.m.

Palmer, a dentist from Minnesota, is unlikely to have guessed what impact his actions would have on the world. Three weeks later, the killing of Cecil was reported in *National Geographic*. The next day, several international celebrities, including Ricky Gervais, Sharon Osbourne, and Ricky Martin, tweeted about it. The day after, a diatribe by late-night TV host Jimmy

Kimmel triggered an outpouring of public outrage, leading to protests outside Palmer's dental office.

By the end of July, less than a month after Cecil's death, around 12,000 distinct news sources were reporting the story. One of the locations impacted by the tsunami of public concern was my hometown in England, where Oxford University's Wildlife Conservation Research Unit (WildCRU)—a group of scientists and conservationists—was suddenly deluged by 4.4 million visitors to its website. Most of them simply wanted to know what they could do to help.

The founder of WildCRU, David Macdonald, is one of my friends and colleagues at Oxford University, where I am a professor of social anthropology and the director of the Center for the Study of Social Cohesion. Macdonald was overwhelmed by the sudden public interest. After years of trying to raise public awareness about the plight of large cats and other endangered species worldwide—Macdonald's group had in fact been tracking Cecil since 2008—here was a sudden upsurge of popular concern.

A question for Macdonald was how to turn Cecil's death to the advantage of WildCRU's conservation efforts. The question from my perspective was: What was it about Cecil's death that motivated people to want to support lion conservation? Would this commitment evolve over time?

My thinking was this. If we could understand what leads people to want to help lions survive and flourish in the wild, maybe we could understand better how to help humans help each other.

One of the greatest puzzles of human evolution is why we sacrifice valuable resources to help others. We know that many other species will cooperate when it's in the interests of individuals to do so. For example, many animals defend their offspring because they carry their genes. Some birds flock together to better protect themselves from predators.

But humans go one step further. Under the right circumstances, they will endure great personal costs to advance the interests of complete strangers. And here, following the death of Cecil, was evidence that love of others could be extended across the species barrier, with thousands of members of the public all around the world clamoring to give time and money to help protect big cats living thousands of miles away. But why?

My long journey to understand why humans will make sacrifices for others began in my early 20s, when I went to live for two years deep in the rainforest of Papua New Guinea with a tribe whose language had never been written down, who had no electricity and no running water, but who had a very rich culture and seemingly unbounded love of their fellow human beings.

The meager amounts of money they earned from selling cash crops at markets many miles from their gardens were not enough to live on. People met their subsistence needs mainly by foraging in the forest and raising crops in their gardens. What little money they had was donated into

a collective fund to pay for such things as medicines for the community, especially to treat malaria, which was widespread in the region and claimed the lives of many. But when my fellow tribesmen heard the news of a cyclone striking Queensland, Australia, they were determined to give away most of the money they had collected over the years to provide them with assistance, even though the Australians affected by the natural disaster were mostly well-insured and supported by skilled emergency services and government aid. Again, the question was: Why?

THE LION IN US The outpouring of grief over Cecil, a 13-year-old lion in Zimbabwe killed by a trophy hunter, caused anthropologist Harvey Whitehouse to wonder: "If we could understand what leads people to want to help lions survive and flourish in the wild, maybe we could understand better how to help humans help each other."



If lions had a say in it, they would probably favor conservation that didn't allow killing members of their prides.

I emerged from my fieldwork convinced that the answer lay in strong forms of social cohesion. In its very strongest expressions, this social cohesion was rooted in the intuition that we all share something very precious—a collective inheritance of sorts. In some cases, this shared inheritance was understood in terms of our bodies, commonly conceptualized in New Guinea in terms of ancestral bones. My fellow Englishmen called it shared blood. Enlightened by science, most of us around the world believe this mysterious stuff is present in our genes. But whatever surface concepts we happen to use, psychologically it is the essence of kinship.

There is also another kind of inheritance that creates intense cohesion in human groups—and that is the sharing of life experiences that are essential not to our bodies but to our sense of self. Psychologists refer to the traces of these experiences in our brains as “episodic memories.” They are the events we collect and recollect later as life-changing and self-defining. When we share such experiences with others, we become strongly bonded to them.

After living in the New Guinea rainforest, I became convinced that both pathways to group-bonding could be created through emotionally intense rituals and ideas about shared ancestry. However, it was just a theory that needed to be tested. To do that, I needed a way of measuring cohesion, that seemingly elusive mental and emotional state that made us willing to sacrifice for the good of the group. Then—to my delight—such a measure was created by a team of psychologists from Texas and Madrid. They called it “identity fusion.”

Identity fusion is a very strong form of social cohesion capable of motivating extreme forms of self-sacrifice and pro-group action. It was measured by showing people pairs of circles, with varying degrees of overlap. Participants in these studies were told the small circle in each pair represented you and the big circle represented your group. These pairs of circles were placed in a sequence. The first pair showed the little circle (you) and the big circle (your group) as separate. The next pair showed the two circles slightly overlapping. In the next pair, the circles overlapped a bit more. And so on, until the last pair on the right showed the little circle entirely enclosed by the big circle. Participants were then asked which pair of circles best characterized their relationship to the group. Those who chose the one on the right (little circle entirely enclosed by the big circle) were said to be “fused” with the group.

Over the next decade, I collaborated with the scientists who designed the fusion measure, and we discovered that highly fused individuals were willing to make great sacrifices for the group—even to fight and die for each other. Testing this theory took me into the heart of Libya’s revolutionary battalions in 2011. It also led me to run surveys with passionately loyal supporters of groups all around the world, including convicted terrorists, religious fundamentalists, football hooligans, and war veterans. What we have learned about the causes and consequences of fusion has allowed us to develop research that could help identify would-be violent extremists and perhaps even predict which of the world’s most authoritarian leaders will be next to use violence against their neighbors.

But fusion does not need to be a deadly force in human affairs. I asked Macdonald if I could run a longitudinal study with a sample of the many thousands of people wishing to make donations to WildCRU. He agreed. And so we designed and ran a survey with a sample of those donors. One of our goals was to measure how “fused” they were with Cecil, and how this impacted willingness to donate money to lion conservation. In line with many other studies we had conducted over the years and around the world, we found that shared, personally transformative memories of learning about the killing of Cecil lay at root of feelings of fusion and prosocial action (in the form of donations). But one aspect of our theory that we hadn’t tested before was that reflecting on such memories would enrich their significance and contribute to fusion over time.

To find out whether reflection on Cecil’s death was indeed driving fusion among his supporters, we continued to collect data. Our hypothesis was that the negative emotions triggered by Cecil’s death would generate fusion with Cecil himself and, in turn, with supporters of lion conservation working for WildCRU. Our data confirmed this. What’s more, fusion to WildCRU increased over the months following Cecil’s demise among those who reflected on the lion’s death, and who incorporated the event as central to their own life histories.

Cecil’s death was reported in at least 127 different languages across countries both rich and poor. Clearly, the story triggered something meaningful and enduring for many people around the world. And given that the lion’s suffering created fusion across the species barrier, it also raised another intriguing possibility that most group-centered movements do not. It made us wonder whether we could fuse not only with a particular nation, religion, ethnic group, or other imagined community but potentially with something greater still—perhaps, with humanity at large.

In a spate of recent studies, we have shown that appreciating how we are all descended from common ancestors or that certain core experiences are shared by everyone, can move us to act on global problems. For example, our research has demonstrated that perceptions of shared experiences of motherhood are associated with higher levels of fusion with other mothers

all around the world, reflected also in willingness to donate money to them.

If humans and lions could unite, what would be their collective goal? I don’t think it would be simply to abolish trophy hunting. Sadly, it is not only rich tourists who benefit from it. In fact, some argue that the revenue from sustainable trophy hunting may contribute both to lion conservation and to the impoverished communities in the regions of Africa where lions are hunted. However, if lions had a say in it, they would probably be in favor of conservation efforts that were funded by some mechanism other than the killing of members of their prides. Poorer communities in the vicinity of Hwange National Park (and others like it) would probably also welcome alternatives to trophy hunting to secure an adequate income and manage the risks of lion attacks.

In 2015, Cecil’s killing galvanized lawmakers in Europe and the United States to revive dormant wildlife laws and propose new bills to prevent citizens from importing lion and other wildlife trophies. A 2017 study that analyzed the impact of Cecil’s death on policy found the initial outrage didn’t drive most of the new bills into law. But a ban on the importation of lion trophies was announced in the Netherlands and France. Two states in the U.S., New Jersey and Hawaii, adopted laws that prohibited the importation, sale, and trade of lion (and 10 other species) trophies. More than 40 airlines introduced new restrictions on the transportation of wildlife trophies.

The way we manage lion conservation today will lay foundations that our children and cubs alike will inherit for generations to come. The challenges involved in nature conservation—like many other global cooperation problems—fall to humans to resolve. The question is whether we can harness the fusion created by the death of Cecil and other forms of shared experience to establish more effective and enduring methods of managing our collective inheritance. ☺

HARVEY WHITEHOUSE is the author of *Inheritance: The Evolutionary Origins of the Modern World*, recently published in the U.K. and the U.S. He is an anthropologist and the director of the Center for the Study of Social Cohesion at the University of Oxford.



Feeling Gravity's Pull

Two theoretical physicists have a lively conversation about how abstract concepts can feel down-to-Earth

BY FOTINI MARKOPOULOU



MET CLAUDIA DE RHAM nearly 20 years ago at Perimeter Institute for Theoretical Physics in Waterloo, Canada. I was one of the founding faculty members, working on quantum gravity, trying to figure out how to put gravity and quantum theory together. Claudia arrived as one of our postdocs in theoretical cosmology, also looking at how the universe evolved and its fundamental laws. We didn't interact much back then, even though we were among the few women at Perimeter. The institute was expanding fast, and everybody was very busy. I always wanted to spend more time with Claudia, because I knew she was not only a physicist but a pilot, a diver, and went all the way to the final stage of the European Space Agency astronaut program.

I left Perimeter and quantum gravity in 2010 and I am now in New York City, while Claudia eventually took up a position at Imperial College London. She is now known for showing that massive gravity works. That's a modification of gravity where a graviton, the hypothetical particle of gravity, gets a mass, meaning that it propagates in speeds lower than the speed of light. At large distances, this tweak adds up and can explain the accelerated expansion of the universe without resorting to mysteries like dark energy. The problem was that we thought this wasn't a legit move because it badly violated certain conditions (known as no-go theorems) that made it mathematically inconsistent. Claudia and her collaborators showed that this was a misreading of the constraints, restoring massive gravity as a possible solution for big problems and opening a new arena for others to explore.

Luckily for me, she also wrote a lovely book, *The Beauty of Falling: A Life in Pursuit of Gravity*, and the world is a small place. I decided to take up the conversation we never had. We sat down for two video interviews and compared notes on working in the world of theoretical physics and how the practice of science is merging intuition and play with abstract concepts and equations.

Gravity is unlike any other force because everything feels gravity. That's beautiful, but it makes gravity hard to handle. Does your work make gravity a bit more normal, like the other forces?

Yes! We have gravity on a pedestal, so perfect it will connect to everything equally. Massive gravity switches some of this off, there is a range where this principle holds, then it's had enough. It becomes like the other forces. It brings spacetime down to earth too, it's simply the reference frame for whatever you want to say. There is no notion of pure spacetime just by itself as in general relativity.

That pure spacetime, a universe with no matter, causes much of the trouble in quantum gravity, too. I never understood why we are so committed to this idealization. Why can't we say that this is not the universe we live in, our world has matter, isn't it great that matter helps us solve problems? You get much resistance if you advocate for this.

That resistance was very much my experience in my field, too. There is a great aspiration for the most abstract, the most grandiose. The bigger the symmetry group, the better. I saw it as natural as to set up our canvas or set up a box, the real-world context that we work inside. That's what physics is. We lay our tools on the table and set them up to start the conversation. Without that, it can be disconnected from reality.

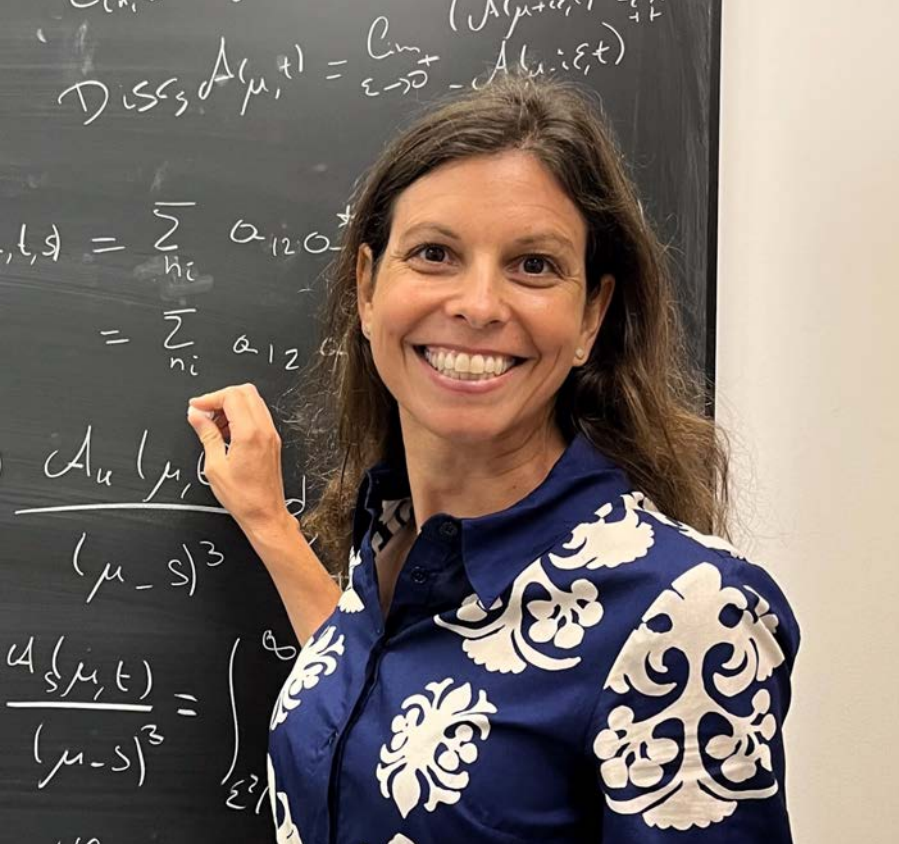
You spent a lot of time in no-go theorems. That's not a place where we hang out much. What was it like?

I am not one of these people who say, "I have this crazy idea that will change the world and I am going to ruin my career pursuing it." No-go theorems exist for a reason. They tell you that under clear and natural assumptions, certain things cannot happen. The only reason I started looking at them more closely is because we had an example that didn't fit. That was very confusing. You have a logical proof for how things must happen and an example that doesn't want to do that. This told us that there must be a way to evade the theorem. Then you spend hours and hours going step by step to identify where your example doesn't fit the no-go theorem and what is missing in the theorem.

It's always about perspective: If you follow the theorem linearly, you end up with a certain outcome. It's only with a little leap that you land elsewhere. Then you understand the physics better and see that the assumptions in the theorem were a bit too strong.

I'll ask you a question I hate when others ask me: How do the different strands of your life relate?





PHYSICS TAKES FLIGHT

Doing physics is like flying a plane, says Claudia de Rham, also a pilot. “You learn how to fly the plane logically, but it has to become second nature ... It’s the same in physics. It has to become second nature, and it is building on your own nature, you bring your own creativity into it.”

Now that you’ve been there, have others found more ways to open up this space?

Yes. There has been a lot of work motivated by ours. When there is a new level in the game people want to play it, plus you can export these techniques to other higher-spin particles. This is where the real fun is! It is not about massive gravity per se, it is about understanding the underlying structure of reality and opening up the possibilities.

You said that questioning a no-go theorem wasn’t a crusade to change the world, it was just being confused about something. I think that’s how it happens all the time.

People ask, “When you understood how it works, was it a Eureka moment?” It’s the opposite, it’s “I was stupid before.” When you understand it, it is obvious. You don’t even think it’s interesting anymore. You think that everyone will say “It’s obvious, let’s move on.”

So true! First, it’s “I must be stupid,” then “it’s obvious,” and then “I don’t even have a paper I can write because it’s all obvious.”

I never felt, “Oh wow, I am on top of it now! Now I have something I can give!” I always feel like I was stupid and confused before, and now I understand why I was confused but it doesn’t make me feel special. What is fun is putting the pieces together. The end of the process doesn’t feel like achieving a big milestone.

Can we take a moment to make fun of the standard question: “Is it frustrating to have so many questions and so few answers?” Which is like asking if I mind that every time I eat a chocolate, two new ones take its place.

It is a misunderstanding of why we do what we do and how we do it. It’s how scientists are portrayed, all about being right, about knowing something. It’s the opposite, it’s about *not* knowing something and finding out that’s fun. Maybe people should try it and see how it feels.

In case anyone gets the wrong impression from the ease with which you describe being confused, you are a pilot and a diver and made it to the final stage of the astronaut selection process of the European Space Agency. I remember how dead set on it you were when we were both at Perimeter. Your book tells how your astronaut dreams were dashed when the ESA found traces of latent tuberculosis. Then the chapter ends. You tell us you received the message with the news, then nothing.

There is nothing. I read it as I was boarding a flight to Canada. I went through all the denial and negotiation stages on that flight. By the time I landed it was “OK, this is it now.” The flight was the transition. That the rejection was due to medical, not psychological, reasons was helpful. The TB wasn’t within my control. I just had to move on.

The build up to the rejection note was very intense, it was a painful and intrusive week. I was the only woman in our astronaut cohort and there were so many intrusive tests I had to do because I am a woman. I can imagine analogous tests for men that are also intrusive but, somehow, they didn’t think of doing such tests for men. As long as there is potential, you tell yourself you can get through this and after it it will be fine. And now there was a clear transition. It wasn’t a “welcome to the rest of my life.” I literally landed in a different place. It was quick in that sense, not like in academia where you apply for positions and are left waiting for six months.

I’ll ask you a question I hate when others ask me: How do the different strands of your life relate? What’s the connection between wanting to be an astronaut and being a physicist?

There was never any doubt in my mind that it is all curiosity-driven, setting yourself up in an environment to probe nature. As a kid, you see it more clearly, you dive into your environment with your whole body because you want to probe it. As you grow wiser, it becomes a more mental exploration, asking ourselves questions as opposed to going somewhere physically. The astronaut is part of the exploration and physics is the same thing: curiosity-driven.

It’s not that I wasn’t curious about other things. My Ph.D. was a terrible time, and I thought there was no way I was going to continue in theoretical

It’s so interesting because how gravity feels to you is not the same as how it feels to me.





DOUBLE STANDARD Most physicists work by relying on their feelings, says Fotini Markopoulou. “But talking about it is tricky. When my Ph.D. supervisor talked like that, he was seen as a wise elder, but a woman will be labeled ‘intuitive’ in a derogatory way. It can be depleting if you have to watch what you say.”

physics. Maybe biophysics or other types of exploration. To my mind, these are not very different. It is still driven by curiosity. I feel very fortunate that I like doing these calculations and I can do it for a living. I find it very peaceful, meditative. It is a structure, you can follow things through, and they will tell you something, a story about themselves. There is creativity, but it comes in by itself as you look at those things in different ways. I would have loved to be an artist, but I am rubbish at it. This is the best artistic thing I can do.

What does curiosity feel like to you?

It is very playful, very candid. It can seem that when something doesn't work it is very frustrating and we get away from that, we don't like it. Curiosity is the opposite, it's the embracing. You see something that doesn't work, doesn't match your preconceptions, and rather than being scared by it, you see it as a light that you are drawn to. You do not know where it will lead you and it is different from what you are used to, but there is the appeal of something that doesn't quite fit. That's what I would say curiosity feels like.

It is playful though, because it is teasing you. It pushes you out of your comfort zone. You have to make fun of yourself, accept you will not have control and try to play with this unknown, try to make progress together.

You often write that gravity is playful, playing, and also that we, scientists, are playing. Science is often labeled as “useful” or “true” and play is the opposite of utility. Do I understand correctly that by “play” you mean engaging, opening your eyes, that this is the way to find new things?

Exactly. Play allows you to explore, and then you find something that you would have never thought is possible.

You write about how gravity tastes or feels. We spend so much time with gravity that we do taste it, feel it, play with it. You also write about flying planes, that as a pilot you put your feelings aside and use logic but you don't fly with just logic. You feel the plane, right? There is a lot of instinct in both. You learn to build your intuition because you have to rely on that intuition. You learn how to fly the plane logically but it has to become second nature. You have to absorb it, to adopt it so completely that in an emergency, when everything is going

COURTESY OF FOTINI MARKOPOULOU

crazy, your intuition will drive you to the right direction. We have natural survival instincts to start with, but building harmony between them and the plane is a process you have to go through. It's the same in physics. It has to become second nature, and it is building on your own nature, you bring your own creativity into it.

The plane becomes an extension of your body, and it works similarly with abstract stuff too, no? A category theory diagram on my blackboard is just as viscerally real to me as the vibration of the drill I use when I build stuff. Absolutely. It's like people who play chess and don't need the chessboard to be there, or even the opponent. It takes a life of its own. I do feel like that, especially for massive gravity. It is like a friend. It is very fragile and it will disappear at some point and that's fine. It has its flows. You know this from the beginning and you try, like for a friend, to understand it, to learn from it, let it develop a little bit and see how much you both can get out of that. It's "OK, you are sick here, how can I help you? How can I move you forward in a direction that would be helpful?" And at some point you have to let it go. But it does provide you with feelings. These are not just words, not just analogies. They are part of the story, it is how you see the system.

I think most physicists work this way, but talking about it is tricky. I wonder if some of the diversity issues in our field, especially with women, hinge on this. When my Ph.D. supervisor talked like that, he was seen as a wise elder, but a woman will be labeled "intuitive" in a derogatory way. It can be depleting if you have to watch what you say.

I know exactly what you mean. Can you allow yourself to show more of how you really do science? That it's not just a hard logical process but it's also feeling your way and having human stories for it? Some people are allowed to, depending on others' preconceptions, others risk being taken less seriously if they show this. This has a cost, how much of yourself is in the message and how it's valued or devalued really matters.

Which is a loss because science relies on sharing what you've seen in your travels, and you are redacting part of the story.

And also because there is a history there, and we've been channeled to think in a particular way, in terms of what fits the format of a paper. If someone allows themselves to go outside of that accepted routine and bring in some different values, they are unlikely to be perceived well. I can tell you, I had much feedback on the book of, "Why should we care about your experience, it has nothing to do with the science, why should anyone be bothered with

There's no such a thing as "truth." We simply embrace what makes sense right here, right now.



that?” But I am not a physicist 9 to 5, following the rules imposed by the fathers of whatever, and after hours I will be a wife and a mother. Every single symbol has a character in my mind, and they play together and make a story. It would have been impossible to write a real book that said what I wanted to say without that human part. But I can see that it triggers the “Why do you allow yourself to do that?” response.

That’s the belief that science is descriptive, not normative. Ideally disembodied. The Lord speaks through you, so the more disembodied the better.

I’d start with the normative side of things. Being part of it. If you put yourself in it, you can’t help but change things. Maybe that’s the difference with some of my colleagues who feel “this is the truth, these are the equations.” They do not see themselves in them at all.

I don’t get that “here’s the truth.” All theories will eventually be superseded. It’s not rational.

I can’t talk for them but I think there is a beautiful ability—a strength, really—to believe that it will be wrong eventually. For a little while, we can live in the luxury of being shielded from failure, even though we are very aware it will come at some point. There’s no such a thing as “truth.” We simply embrace what makes sense right here, right now, while knowing that at some point we will need to go deeper. But for now, we are protected from needing to worry about the points that will be wrong.

Sigh. Let’s go back to writing papers. This embodied experience of reaching out and touching what you are devoted to studying is hard to share in words. Papers and their strict format are so limiting. A

book like yours goes a bit further. It’s so interesting to me because how gravity feels to you is not the same as how it feels to me. It’s not fragile to me, but I know what you mean when you say it has a sense of humor. Hanging out with gravity is like watching Eddie Izzard, the same trippy feeling that the world makes more sense upside down.

It’s important that everyone feels it slightly differently, that’s how everyone gets a slightly different expertise and a slightly different way to see things. We use the same math and the same logic, but the way we make these small leaps and say “if this happens, then it will behave like that,” there is a level of feeling. You feel for the system itself, how it will behave and how you can challenge it.

It’s about not knowing something and finding out that’s fun. People should try it and see how it feels.



Yes, those little leaps, like getting out of the no-go theorem, come from feeling your way, the curiosity. The papers we write do not tell that story.

There is a translation process with many steps between how you relate and connect to your subject at the human, emotional level, and a talk or a paper which is very formal and structured. There are people close to you, usually your long-time collaborators, with whom you can make contact without having every word in the story. Outside that circle much gets lost.

You had a comment about having mixed feelings about words in your early life.

I find it really hard, even now. Words are like a discretization. You have these complex thoughts, and you need to pixelize them and put them in a compartment to fit them to a classification that is not exact. Every time I give a talk, I explain the same thing differently because the words are never quite right. Every attempt is an approximation to what it feels. When you write a paper, people get an impression of what you want to say and it's also never quite right. You do what you can. It's when you talk to the author that you start seeing how they made the connections between different things.

The little leaps that feel like confusion, and you can only work out afterward.

We can only make models of what we see. How you decide to describe what you are seeing has a life of its own. When you say it is sick, of course it is not. It's that gravity feels like a ghost, a representation of nature for a given regime, and that ghost, which isn't the truth, it isn't something fully fundamental. It has a way to start, to develop and behave a certain way in some situations. So it has a kind of life. If it's sick it's because this isn't a good way to think about it and you'll have to discard it for another model. But I don't think of it necessarily as another model, you actually evolve. Everything evolves.

People like to say, "you have Newton's theory, and along came Einstein and proved Newton wrong and came up with a new theory, and Newton was wrong." But it's not like that. There is so much understanding in all of them. It keeps on taking life and it keeps on taking roots in itself, so the core is still there. You evolve it. We are making a painting of nature, and confronting it against nature, it takes a life of its own. You discover

new ways to use the brushes. I imagine it is like that for an artist. It is not that they are projecting an image on the painting, the painting is calling for something. There is a void that needs to be filled.

My parents were both sculptors and I had the most useful conversations with my mum. She would have sculpture in mind, and I had theoretical physics but it's very similar, creating something that looks right from all angles. It seems impossible, so where does it come from? She had to ingest the situation until her hands made the sculpture. We must lack language because it is not a mystery. It's like flying a plane and needing to get to the level where it feels part of you. For a plane we understand it, but when it is about physics, it seems a mystery. But it's the same thing, spend time with it and then your hands will do it.

I completely agree. For me, sculpture would look very much like a mystery. I can't understand how they come up with what they do, how they can have that vision and realize it. It's impossible for me to imagine how this would happen. But in physics it is very natural, there is no mystery at all.

If someone was giving out grants to do something that is not work and is not useful, but it gives you joy, what would you pick?

I would still like to go to space! I would love to see the Earth from above. I would love to be in free fall. Observe things, be part of something. Anything else has a finality to it. This is enjoying the moment without thinking it will stop. ☺

FOTINI MARKOPOULOU is a quantum gravity physicist and former founding faculty at Perimeter Institute for Theoretical Physics. She's a design engineer and was CEO of Empathic Technologies, merging neuroscience and embodied technologies. Currently with ComplexReal, she works on metrics, measuring and data, and the role of science in culture.

HARPER'S

M A G A Z I N E

Findings

A mother is 4.6 percent more likely to give birth in the same month she was born.  Half of all beef consumed in the United States is eaten by 12 percent of adults.  The playing speed of a metal guitarist directly correlates with his intrasexual competitiveness but not his mating success.  Scientists advised against consuming hypersexual zombie cicadas infected with psychoactive fungus.  A metal scar on the surface of the white dwarf WD0816310 indicated that it has cannibalized other bodies in its orbit.  Dwarf rock-wallabies were found to have unusually large teeth. "If I were a vegetable," said a skull-shape researcher, "I would not mess with a pygmy rock-wallaby." 

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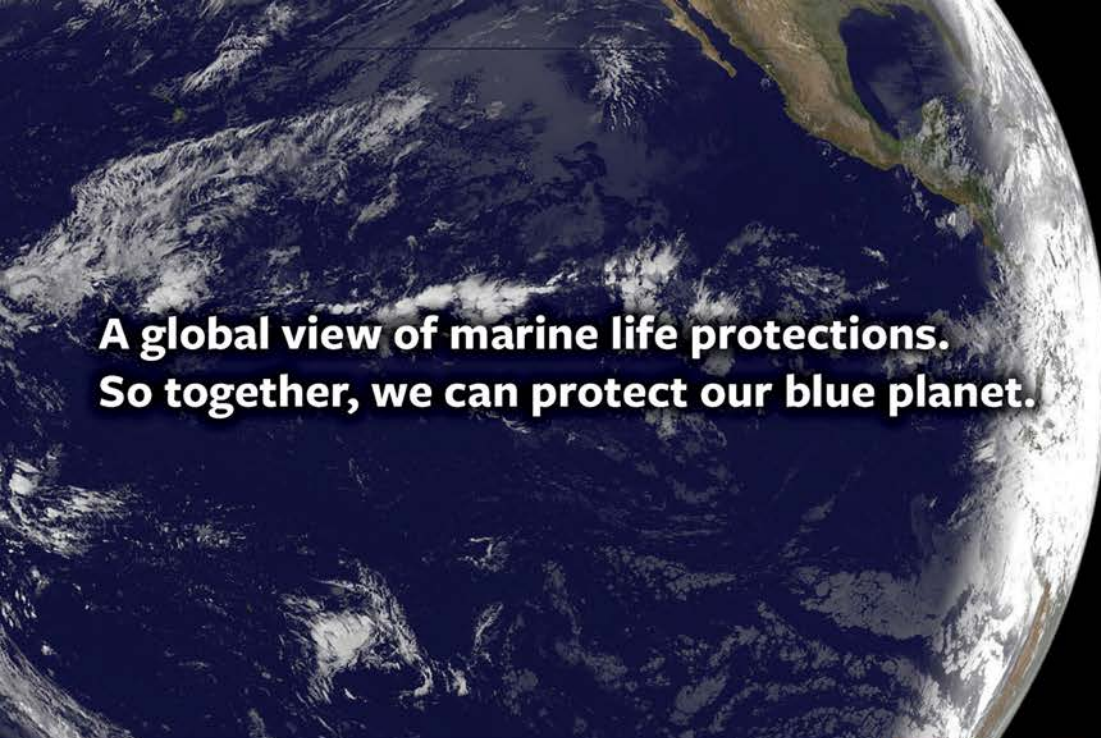
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**A global view of marine life protections.
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Navigator

Navigator is a free, interactive map of regulatory information for over 21,000 managed saltwater and coastal areas worldwide, including the high seas. As the most comprehensive database of marine protections and their boundaries, Navigator can be used to help estimate progress towards 30x30 through its Level of Fishing Protection (LFP) scoring system.

Together, we can preserve special ocean places for future generations.



protectedseas

NAVIGATOR

GUIDE TO OUR REGULATORY SEASCAPE



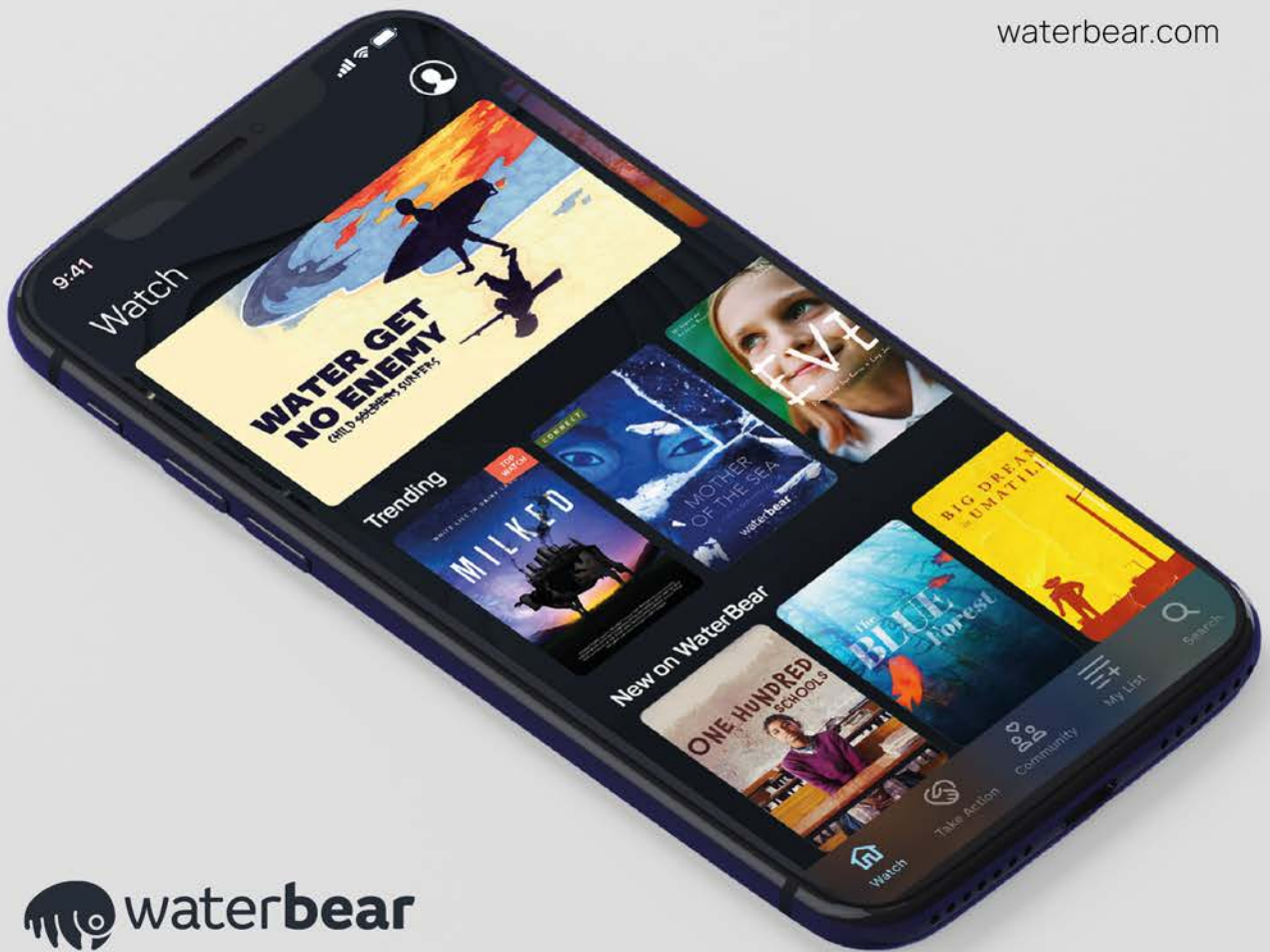


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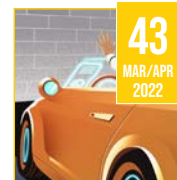
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Our Magnificent Ocean

*Richard Powers on his three greatest revelations while writing his latest novel, **Playground***

BY RICHARD POWERS

1

THE OCEAN REPRESENTS 99 PERCENT OF THE BIOSPHERE

Over the last decade, I've been trying to write novels that resituate human beings inside the interconnected webs of a living planet. After exploring dense forest networks in *The Overstory* and confronting mass extinction and ecoanxiety in *Bewilderment*, I realized that I needed to turn my attention to the immense wellspring of all life on Earth: the oceans.

Like most people, I knew from way back in grade school that the oceans cover more than 70 percent of the planet's surface. And I had a good sense of their depth—on average about 12,000 feet. What I didn't appreciate was just how much livable space that represented, compared to terrestrial habitats.

Comparing the inhabitable terrain of the ocean to that of the land yields a startling statistic: The ocean represents something very close to 99 percent of the biosphere. Spread out as far as we might, we humans still can't occupy more than 1 or 2 percent of the livable space on Earth.

2

I FELL IN LOVE WITH MANTA RAYS

There are more kinds of fish than all the mammals, birds, reptiles, and amphibians put together. Three fifths of every creature with a backbone is a fish. Their ability to sense the world exceeds our own in many ways.

It stunned me to read about their powers of cognition. Swimming over a tidal pool at high tide, a goby can memorize the entire layout of the terrain after only one exposure. So can a frillfin, calculating precisely where the pools will be at low tide. Archerfish can learn a skill by watching others at a distance, an ability known as perspective-taking.

I fell in love with manta rays, whose cognitive abilities went way beyond what I ever imagined. They have the largest brain of any fish, one of the two or three largest on Earth relative to their body size. They are exceptionally playful and curious, and they practice coordinated social behavior. Mantas even display contingency checking and other signs of self-awareness in front of mirror, passing the mirror self-recognition test. While the full significance of such tests are controversial, it's worth pointing out that many kinds of primates and very smart mammals, including dogs, cannot pass them.



PHOTO BY KEVIN BERGER

3

ALMOST ALL OF THE OCEAN IS UNEXPLORED

What impressed me the most about the oceans was how little we know about them. According to NOAA,

we have explored only 5 percent of the oceans and mapped only about one quarter of the seafloor in high resolution. Scientists estimate that roughly 1 million species live in the oceans (excluding microorganisms, which would push the total far higher). Of that number, two thirds or more remain to be discovered or described. Almost 2,000 new species are being identified every year.

Our greatest and most catastrophic ignorance is how little we know about our own impact on a place we once thought we could never much alter. Some scientists talk about “dark plastic,” estimating that 99 percent of the plastic we have put into the ocean can't subsequently be located or traced. Just half a dozen years ago, researchers discovered whole new ecosystems based on floating plastic debris, replete with coastal creatures floating in the middle of the ocean.

Maybe my biggest revelation was a bit of wisdom that Polynesians have known for a very long time. In her essential book, *How the Ocean Works*, Helen Czerski quotes the Hawaiian phrase, *He moku he wa'a, he wa'a he moku*. “A canoe is an island, and an island is a canoe.” This unknown water planet is an island in the emptiness of incalculable space. It's also our canoe. ☺



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